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Stack Sampling Technical Information
A Collection of Monographs and Papers
Volume III

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16. ABSTRACT

"Stack Sampling Technical Information" is a four-volume collection of monographs and papers which have been compiled by the Emission Measurement Branch, ESED, OAQPS. The information specifically relate to current EPA test methods and compliance test procedures. The data presented in some of these documents have served as the basis for a number of revisions made in the EPA Reference Methods 1 through 8. Several of the documents are also useful in determining acceptable alternative procedures.

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A Collection of Monographs and Papers

Volume III

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Stack Sampling Technical Information
A Collection of Monographs and Papers
Volume III

Emission Standards and Engineering Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

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PREFACE

The Clean Air Act of 1970 requires the Administrator of the Environmental Protection Agency to establish national emission standards for new stationary sources (Section 111) and hazardous air pollutants (Section 112). The development of these emission standards required the concurrent development of reference test methods and procedures. The reference test methods and procedures are published in the Federal Register along with the appropriate regulations.

From time to time, questions would surface concerning the methods and procedures. In many cases, specific studies would be needed to provide informed, objective answers. The papers and monographs resulting from these studies were usually distributed to people involved in emission measurement; a major method of distribution has been the Source Evaluation Society Newsletter.

To provide a readily available resource for new and experienced personnel, and to further promote standardized reference methods and procedures, it has been decided to publish the papers and monographs in a single compendium. The compendium consists of four volumes. The Table of Contents for all four volumes is reproduced in each volume for ease of reference.

Congratulations and sincere appreciation to the people who did the work and took the time to prepare the papers and monographs. For the most part the work was done because of personal commitments to the development of objective, standardized methodology, and a firm belief that attention to the details of stack sampling makes for good data. The foresight of Mr. Robert L. Ajax, the former Chief of the Emission Measurement Branch and now the Assistant Director, Emission Standards and Engineering Division, in providing the atmosphere and encouragement to perform the studies is gratefully acknowledged. The skill and dedication of Mr. Roger Shigehara, in providing personal supervision for most of the work, is commended.

Don R. Goodwin
Director
Emission Standards and
Engineering Division

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THERMOCOUPLE CALIBRATION PROCEDURE EVALUATION

Kenneth Alexander*

Introduction

The Federal test methods[1] published in the August 18, 1977, Federal Register require that thermocouple-potentiometer systems be calibrated after each field use. Above 405°C, an NBS calibrated reference thermocouple-potentiometer system or an alternative reference, subject to the approval of the Administrator, is specified for the comparison. Since the calibration procedure requires the use of high temperatures in the laboratory and the use of expensive reference thermocouples, a study was conducted to determine whether extrapolated values from low-temperature calibrations would provide sufficiently accurate values at the high temperatures.

The purpose of this paper is to report the findings of the study and to establish a simplified calibration procedure.

Equipment and Procedure

Six chromel-alumel (type K) thermocouples and one potentiometer with readout were selected for calibration. ASTM mercury-in-glass reference thermometers and an NBS calibrated platinum-rhodium (type S) thermocouple-potentiometer were used as the temperature references.

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The following procedures were used in calibrating the thermocouples:

1. For the ice point (32°F) calibration, crushed ice and liquid water were placed in a Dewar vessel to form a slush. The thermocouples were placed in the slush to a depth of not less than 2 inches, and care was taken so that they did not touch the sides of the vessel.

After a 3-minute wait for the system to reach thermal equilibrium, the readout on the potentiometer was observed and recorded. Eight readings were taken in 1-minute intervals. When necessary, ice was added and excess liquid drained off to maintain a temperature of 32°F.

2. For the boiling point calibration a hot plate and a Pyrex beaker filled with deionized water and several boiling chips were used. After the water reached a full boil, the thermocouples were placed in the water to a depth of no less than 4 inches and the system was allowed to equilibrate for 3 minutes. Eight potentiometer readings were obtained in successive 1-minute intervals and recorded. Barometric pressure was also recorded periodically. The temperature of the boiling water was measured concurrently with a reference thermometer to obtain the correct temperature of the water.

3. For higher temperature calibrations, a tube furnace and ASTM reference thermometers (up to 760°F) or the NBS calibrated platinum-rhodium reference thermocouple (above 760°F) were employed.

The tube furnace had a heated cylindrical volume approximately 13 inches in length and a 1-inch I.D.; the volume at either end was opened to the atmosphere.

The highest and most stable temperature was found to be at the center of the oven volume. This is where the tip of the reference device and the tip of the thermocouple were placed. The test and reference thermocouples were inserted into the furnace at least 4 inches. The ASTM reference thermometers, however, which were designed for full immersion, could not be totally immersed in the furnace. A temperature correction[2] was made, therefore, for the length of the mercury shaft that was exposed to the outside of the furnace.

To minimize temperature fluctuations, the furnace was heated 50° to 100° above the desired calibration temperature and then allowed to cool at a rate that the slower responding device could accommodate. When it was clear that both devices were responding to the temperature drop at the same steady rate, temperature readings were recorded at 1-minute intervals until eight readings were obtained. The average of all eight readings was taken as the calibration temperature. Several high-temperature calibrations were made in the range of 600° to 1600°F.

To determine whether the thermocouples lose any of their accuracy or precision at low temperatures after repeated exposure to high temperatures, three thermocouples were successively calibrated at the ice point, boiling point, and approximately 1600°F.

Discussion of Results

Results of all tests are summarized in Tables 1, 2, and 3. Table 1 lists the temperature observed. Table 2 shows the results of constructing an extrapolated curve from only the ice point and boiling point data found in Table 1 by using the least-squares method. The final column in Table 2 shows the percent error between extrapolated and actual values to be always less than 1.1 percent. This is well within the specified accuracy[1] of 1.5 percent of the measured absolute temperature. Table 3 summarizes the tests made to determine the retention of calibration by thermocouples after repeated cycling between high and low temperatures. The percent error between the observed and reference temperatures is never more than 1 percent and rarely above 0.5 percent. Thus, there seems to be no indication that any loss of precision or accuracy occurs by cycling the thermocouples between temperature extremes.

Recommended Procedure

The following procedure is recommended for calibrating thermocouples for field use:

1. For the ice point calibration, form a slush from crushed ice and liquid water (preferably deionized, distilled) in an insulated vessel such as a Dewar flask.

Taking care that they do not touch the sides of the flask, insert the thermocouples into the slush to a depth of at least 2 inches. Wait 1 minute to achieve thermal equilibrium, and record the readout on the potentiometer. Obtain three readings

Table 1: DATA SUMMARY OF THERMOCOUPLE CALIBRATION

I.D. NO. 101		I.D. NO. 102		I.D. NO. 103	
Test temperature, °R	Reference temperature, °R	Test temperature, °R	Reference temperature, °R	Test temperature, °R	Reference temperature, °R
494	492 (32°F)	494	492	493	492
676	675 (216°F)	676	675	674	672
1113	1108 (648°F)	1295	1292	1118	1114
1261	1260 (800°F)	1596	1583	1276	1273
1664	1658 (1196°F)			1537	1537
				1969	1972

I.D. NO. 108		I.D. NO. 110		I.D. NO. 111	
Test temperature, °R	Reference temperature, °R	Test temperature, °R	Reference temperature, °R	Test temperature, °R	Reference temperature, °R
493	492	493	492	493	492
674	672	674	672	674	672
1107	1104	1298	1295	1293	1285
1304	1298	1628	1618	1624	1609
1598	1590	2074	2064		
2012	2018				

Table 2: TRUE REFERENCE TEMPERATURES VERSUS EXTRAPOLATED REFERENCE TEMPERATURE

I.D. NO.	Observed temperature, ^{o}R	Reference temperature, ^{o}R	Reference Temperature Extrapolated From 32^{o}, 212^{o} F (1), R^{o}	% Error Between Actual Reference And Extrapulated Reference
101	1261	1260	1263	0.24
101	1663	1658	1667	0.54
102	1295	1292	1297	0.39
102	1596	1583	1600	1.07
103	1276	1273	1271	0.16
103	1537	1537	1530	0.46
103	1969	1972	1960	1.0
108	1304	1298	1298	0
108	1598	1590	1591	0.06
108	2012	2018	2003	1.0
110	1298	1295	1293	0.15
110	1628	1618	1621	0.18
110	2074	2064	2064	0
111	1293	1285	1288	0.23
111	1624	1609	1617	0.50

Table 3: EFFECTS OF REPEATED CYCLING BETWEEN HIGH AND LOW TEMPERATURES

	I.D. No. 110			I.D. No. 103			I.D. No. 108		
Run	Test temperature, °R	Reference temperature, °R	% Error	Test temperature, °R	Reference temperature, °R	%Error	Test temperature, °R	Reference temperature, °R	% Error
1	493	492	0.2	493	492	0.2	493	492	0.2
2	493	492	0.2	493	492	0.2	494	492	0.41
3	493	492	0.2	494	492	0.41	494	492	0.41
4	493	492	0.2	494	492	0.41	494	492	0.41
5	493	492	0.2	494	492	0.41	494	492	0.41
6	494	492	0.41	494	492	0.41	494	492	0.41
1	675	672	0.45	674	672	0.3	674	672	0.3
2	674	672	0.3	674	672	0.3	674	672	0.3
3	674	672	0.3	674	672	0.3	674	672	0.3
4	674	672	0.3	674	672	0.3	674	672	0.3
5	675	672	0.45	674	672	0.3	674	672	0.3
6	675	672	0.45	674	672	0.3	674	672	0.3
1	2090	2074	0.77	2076	2063	0.63	2069	2063	0.29
2	2110	2100	0.48	2097	2090	0.33	2038	2032	0.3
3	2068	2056	0.39	2063	2056	0.34	2064	2056	0.39
4	2096	2085	0.53	2092	2086	0.29	2094	2087	0.34
5	2382	2374	0.34	2381	2373	0.34	2378	2373	0.21
6	2079	2075	0.19	2080	2074	0.29	2079	2073	0.29

taken in 1-minute intervals. (Longer times may be required to attain thermal equilibrium with thick-sheathed thermocouples.)

2. Fill a large Pyrex beaker with water to a depth of no less than 4 inches. Place several boiling chips in the water, and bring the water to a full boil using a hot plate as the heat source. Insert the thermocouple(s) in the boiling water to a depth of at least 2 inches, taking care not to touch the sides or bottom of the beaker.

Alongside the thermocouple(s) an ASTM reference thermometer should be placed. If the entire length of the mercury shaft in the thermometer cannot be immersed, a temperature correction will be required[2] to give the correct reference temperature.

After 3 minutes both instruments will attain thermal equilibrium. Simultaneously record temperatures from the ASTM reference thermometer and the thermocouple-potentiometer three times at 1-minute intervals.

3. From the calibration data obtained in the first two steps of the procedure, plot a linear curve of observed temperature versus reference temperature. Extrapolate a linear curve from these two points using the least-squares method, and the result will be a calibration curve for higher temperatures (up to 1500°F) accurate to within 1.5 percent on the absolute temperature scale.

4. For even greater accuracy in constructing a calibration curve, it is recommended that a boiling liquid (such as cooking oil) be used for a calibration point in the 300°- 500°F range.

References

1. "Standards of Performance for New Stationary Sources, Revisions to Methods 1 - 8," Title 40, Part 60. Federal Register, Vol. 42, No. 160 August 18, 1977.

2. Weast, Robert C., Handbook of Chemistry and Physics, 54th Edition, CRC Press, Cleveland, Ohio, 1973, pp. D158.

PROCEDURE FOR CALIBRATING AND USING DRY GAS VOLUME METERS AS CALIBRATION STANDARDS

P. R. Westlin and R. T. Shigehara*

INTRODUCTION

Method 5,[1] "Determination of Particulate Emissions from Stationary Sources," and APTD-0576,[2] Maintenance, Calibration, and Operation of Isokinetic Sampling Equipment, specify that a wet test meter be used as the calibration standard for volume measurements. A recent study[3] has shown, however, that a properly calibrated dry gas volume meter may be used in lieu of a wet test meter for calibrating Method 5 equipment. The procedure below outlines the proper calibration steps for preparing a dry gas volume meter as a calibration standard. In addition, the procedures outlined in APTD-0576 for calibration of a dry gas meter in the Method 5 sampling train are modified to reflect the findings of the above mentioned study.

CALIBRATING THE STANDARD DRY GAS METER

The dry gas meter to be calibrated and used as a secondary reference meter should be of high quality and have a scale of 3 liters/rev (0.1 ft^3/rev). A spirometer (400 liter or more capacity) may be used for this calibration, although a wet test meter is usually more practical. The wet test meter should have a scale of 30 liters/rev (1 ft^3/rev) and capable of measuring volume to within $\leq$ 1.0 percent; wet test meters should be checked against a spirometer or a liquid displacement meter to ensure the accuracy of the wet test meter. Spirometers or wet test meters of other sizes

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may be used, provided that the specified accuracies of the procedure are maintained.

Set up the components as shown in Figure 1. A spirometer may be used in place of the wet test meter in the system. Run the pump for at least 5 minutes at a flow rate of about 10 liters/min (0.35 cfm) to condition the interior surface of the wet test meter. The pressure drop indicated by the manometer at the inlet side of the dry gas meter should be minimized [no greater than 100 mm H_2O (4 in. H_2O) at a flow rate of 30 liters/min (1 cfm)]. This can be accomplished by using large-diameter tubing connections and straight pipe fittings.

The data collected for each run include: approximate flow rate setting, wet test meter volumes, dry gas meter volumes, meter temperatures, dry gas meter inlet pressure, barometric pressure, and run time. Figure 2 shows an example data sheet that may be used in data collection. Repeat runs at each orifice settings at least three times.

Repeat the calibration runs at no less than five different flow rates. The range of flow rates should be between 10 and 34 liters/min (0.35 and 1.2 cfm).

Calculate flow rate, Q, for each run using the wet test meter gas volume, V_w, and the run time, θ. These calculations are as follows:

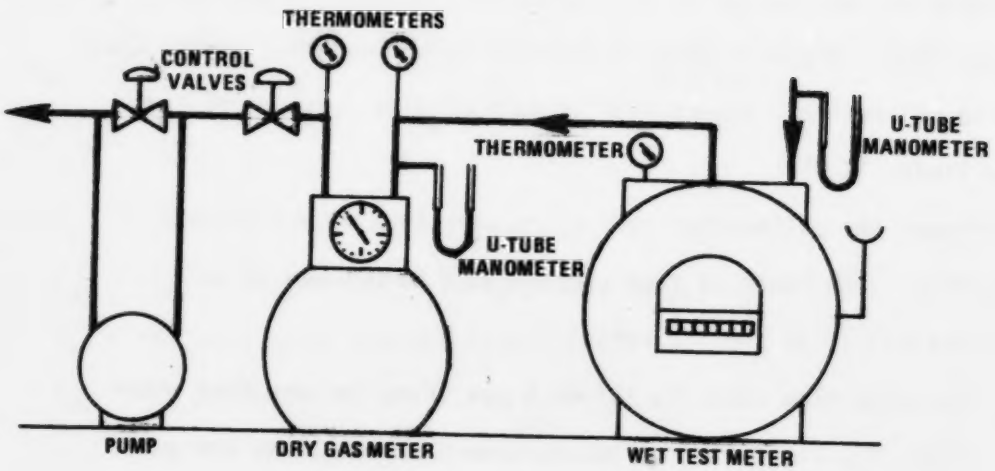

Figure 1. Equipment arrangement for dry-gas meter calibration.

DATE:_____

DRY GAS METER IDENTIFICATION:_____

BAROMETRIC PRESSURE (P_b):_____ in. Hg

APPROXIMATE FLOW RATE ($\tilde{Q}$) cfm	SPIROMETER (WET METER) GAS VOLUME (V_s) ft^3	DRY GAS METER VOLUME (V_{dg}) ft^3	TEMPERATURES				DRY GAS METER PRESSURE (Δp) in. H_2O	TIME (Θ) min.	FLOW RATE (Q) cfm	METER METER COEFFICIENT (Y_{ds})	AVERAGE METER COEFFICIENT ($\bar{Y}_{ds}$)
			SPIROMETER (WET METER) (t_s) °F	DRY GAS METER							
				INLET (t_i) °F	OUTLET (t_o) °F	AVERAGE ($\bar{t}_d$) °F					
0.40											
0.60											
0.80											
1.00											
1.20											

$$Q = 17.65 \cdot \frac{V_s}{\Theta} \cdot \frac{P_b}{(t_s + 460)}$$

$$Y_{ds} = \frac{V_s}{V_{dg}} \cdot \frac{(\bar{t}_d + 460)}{(t_s + 460)} \cdot \frac{P_b}{\left(P_b + \frac{\Delta p}{13.6}\right)}$$

Figure 2. Example data sheet for calibration of a standard dry gas meter for method 5 sampling equipment (English units).

$$Q = 0.3855 \frac{P_b}{(t_w + 273)} \frac{V_w}{\Theta} \qquad \text{(SI units)}$$

Equation 1

$$Q = 17.65 \frac{P_b}{(t_w + 460)} \frac{V_w}{\Theta} \qquad \text{(English)}$$

Calculate the dry gas meter coefficient, Y_{ds}, for each run as follows:

$$Y_{ds} = \frac{V_w}{V_{ds}} \frac{(t_{ds} + 273)}{(t_w + 273)} \frac{P_b}{(P_b + \frac{\Delta p}{13.6})} \qquad \text{(SI units)}$$

Equation 2

$$Y_{ds} = \frac{V_w}{V_{ds}} \frac{(t_{ds} + 460)}{(t_w + 460)} \frac{P_b}{(P_b + \frac{\Delta p}{13.6})} \qquad \text{(English)}$$

Where:

Y_{ds} = dry gas meter coefficient, dimensionless

V_w = wet test meter volume, liters (ft^3)

V_{ds} = dry gas meter volume, liters (ft^3)

t_{ds} = average dry gas meter temperature, °C (°F)

t_w = average wet test meter temperature, °C (°F)

P_b = barometric pressure, mm Hg(in. Hg)

Δp = dry gas meter inlet differential pressure, mm H_2O(in. H_2O)

Θ = run time, min

Compare the three Y_{ds} values at each of the flow rates and

determine the maximum and minimum values. The difference between the maximum and minimum values at each flow rate should be no greater than 0.030. Extra runs may be made in order to complete this requirement. If this specification cannot be met in six successive runs, the meter is not suitable as a calibration standard and should not be used as such. In addition, the meter coefficients should be between 0.95 and 1.05. If these specifications are met, average the three Y_{ds} values at each flow rate resulting in five average meter coefficients, $\overline{Y}_{ds}$.

Prepare a curve of meter coefficient, $\overline{Y}_{ds}$, versus flow rate, Q, for the dry gas meter. This curve shall be used as a reference when the meter is used to calibrate other dry gas meters and to determine whether recalibration is required.

USING THE STANDARD DRY GAS METER AS A CALIBRATION STANDARD

The sampling dry gas meter shall be calibrated as it will be used in the field; therefore, it shall be installed into the field meter box, if applicable, prior to calibration. Set up the components as shown in Figure 3. Run the pump in the meter box about 15 minutes to warm the pump and other components. Select three equally spaced flow rates for calibration that cover the range of flow rates expected in the field. Then collect the data for calibration. These data include approximate flow rate, orifice setting, initial and final standard dry gas meter volumes, initial and final meter box gas meter volumes, meter temperatures, barometric pressure, and run time. Repeat the runs at each flow rate at least twice.

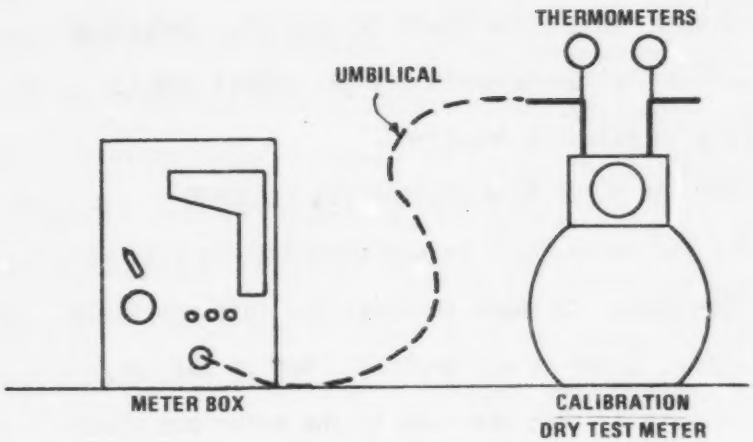

Figure 3. Meter box calibration set-up.

The range of flow rates will depend somewhat on the use of the meter in the field. That is, if the meter is to be used at flow rates between 10 and 34 liters/min (0.35 and 1.2 cfm), then duplicate calibrations should be run at three equally spaced flow rates between these two values.

Determine the flow rate for each run using the standard dry gas meter volume, V_{ds}.

$$Q = 0.3855 \frac{P_b}{(t_{ds} + 273)} \frac{V_{ds}}{\theta} \qquad \text{(SI units)}$$

Equation 3

$$Q = 17.65 \frac{P_b}{(t_{ds} + 460)} \frac{V_{ds}}{\theta} \qquad \text{(English)}$$

Using the curve of Y_{ds} versus flow rate established earlier for the standard dry gas meter, determine the meter coefficient, Y_d, at each orifice setting, ΔH, as follows:

$$Y_d = Y_{ds} \frac{V_{ds}}{V_d} \frac{(t_d + 273)}{(t_{ds} + 273)} \frac{P_b}{(P_b + \frac{\Delta H}{13.6})} \qquad \text{(SI units)}$$

Equation 4

$$Y_d = Y_{ds} \frac{V_{ds}}{V_d} \frac{(t_d + 460)}{(t_{ds} + 460)} \frac{P_b}{(P_b + \frac{\Delta H}{13.6})} \qquad \text{(English)}$$

Calculate an average $\overline{Y}_d$ over the range of operation and calculate a standard deviation for all the calibration runs. The maximum standard deviation should not exceed a value of $\pm$ 0.020. Figure 4 shows an example data sheet that may be used for these calibrations with the necessary calculations. The average $\overline{Y}_d$ should be marked on the calibrated meter box along with the date of calibration and $\Delta H_@$, the orifice setting that corresponds to 21 liters/min (0.75 cfm) at 20° C and 760 mm Hg (68° F and 29.92 in. Hg).

RECALIBRATION OF STANDARD DRY GAS METER

In a recent study[3] a dry gas meter under controlled conditions in a laboratory maintained its calibration within about 1 percent for at least 200 hours of operation. It is recommended that the standard dry gas meter be recalibrated against a wet test meter or spirometer annually or after every 200 hours of operation, whichever comes first. This requirement is valid provided the standard dry gas meter is kept in a laboratory and, if transported, cared for as any other laboratory instrument. Abuse to the standard meter may cause a change in the calibration and will require more frequent recalibrations.

As an alternative to full recalibration, a two-point calibration check may be made. Follow the same procedure and equipment arrangement as for a full recalibration, but run the meter at only two flow rates [suggested rates are 14 and 28 liters/min (0.5 and 1.0 cfm). Calculate the meter coefficients for these two points, and compare the values with the meter calibration curve. If the two coefficients are within $\pm$ 1.5 percent of the calibration curve values at the same flow rates, the meter need not be recalibrated until the next date for

DATE: _____ CALIBRATION METER IDENTIFICATION: _____

METER BOX IDENTIFICATION: _____ BAROMETRIC PRESSURE (P_b): _____ in. Hg

APPROXIMATE FLOW RATE ($\bar{Q}$) cfm	ORIFICE READING (ΔH) in. H_2O	CALIBRATION METER GAS VOLUME (V_{ds}) ft^3	METER BOX METER GAS VOLUME (V_d) ft^3	TEMPERATURE						TIME (Θ) min.	METER BOX METER COEFFICIENT (Y_d)	($\Delta H@$)
				CALIBRATION METER			METER BOX METER					
				INLET (t_{dsi}) °F	OUTLET (t_{dso}) °F	AVERAGE ($\bar{t}_{ds}$) °F	INLET (t_{di}) °F	OUTLET (t_{do}) °F	AVERAGE ($\bar{t}_d$) °F			
0.40												
0.80												
1.20												
									AVERAGE			

$$Y_d = Y_{ds} \frac{V_{ds}}{V_d} \cdot \frac{(\bar{t}_d + 460)}{(\bar{t}_{ds} + 460)} \cdot \frac{P_b}{(P_b + \frac{\Delta H}{13.6})}$$

$$\Delta H@ = \frac{0.0317\,\Delta H}{P_b\,(\bar{t}_d + 460)} \left[\frac{(\bar{t}_{ds} + 460)\,\Theta}{V_{ds}}\right]^2$$

WHERE: $\Delta H@$ = ORIFICE PRESSURE DIFFERENTIAL THAT GIVES 0.75 cfm OF AIR AT 70° F AND 29.92 inches OF MERCURY, in. H_2O.
TOLERANCE - ±0.15

Figure 4. Example data sheet for calibration of meter box gas meter against a calibration dry gas meter (English units).

a recalibration check.

CALIBRATING THE DRY GAS METER FOR METHOD 6 SAMPLING

Method 6,[1] "Determination of Sulfur Dioxide Emissions from Stationary Sources," requires a meter box with a flow rate of about 1 liter/min (2 cfh). A dry gas meter may be used as a standard volume meter for this application, if it has been calibrated against a wet test meter (1 liter/min) or spirometer in the proper flow rate range. For this purpose, a dry gas meter standard need be calibrated at 1 liter/min (2 cfh) and the meter box should be calibrated against the standard dry gas meter at the same flow rate. The calculations are similar to the ones described earlier. Again, the calibrations of the standard meter should be repeated three times against the wet test meter or spirometer. The calibration of the meter box gas meter should be repeated twice. Example data sheets for these calibrations are shown in Figures 5 and 6.

SUMMARY

A dry gas volume meter is calibrated against a spirometer or a wet test meter under controlled conditions. A curve of meter coefficient versus meter flow rate is established and kept with the dry gas meter. The calibrated dry gas meter is then used as a reference meter in the calibration of meters used in field testing.

REFERENCES

1. "Standards of Performance for New Stationary Sources, Revisions to Methods 1-8," Title 40, Part 60. Federal Register, Vol. 42, No. 160. August 18, 1977.

DATE: _____

DRY GAS METER IDENTIFICATION: _____

BAROMETRIC PRESSURE (P_b): _____ in. Hg

APPROXIMATE FLOW RATE ($\bar{Q}$) cfh	SPIROMETER (WET METER) GAS VOLUME (V_s) ft^3	DRY GAS METER VOLUME (V_{dg}) ft^3	TEMPERATURES				DRY GAS METER PRESSURE (ΔP) in. H_2O	TIME (Θ) min.	FLOW RATE (Q) cfh	METER COEFFICIENT (Y_{ds})
			SPIROMETER (WET METER) (t_s) °F	DRY GAS METER						
				INLET (t_{di}) °F	OUTLET (t_{do}) °F	AVERAGE ($\bar{t}_d$) °F				
2.0										
							AVERAGE			

$$Q = 1063 \cdot \frac{V_s}{\Theta} \cdot \frac{P_b}{(t_s + 460)}$$

$$Y_{ds} = \frac{V_s}{V_{dg}} \cdot \frac{(\bar{t}_d + 460)}{(t_s + 460)} \cdot \frac{P_b}{\left(P_b + \frac{\Delta P}{13.6}\right)}$$

Figure 5. Example data sheet for calibration of a standard dry gas meter for method 6 sampling equipment (English units).

DATE: _____ CALIBRATION METER IDENTIFICATION _____

METER BOX IDENTIFICATION _____

BAROMETRIC PRESSURE (P_b): _____ in. Hg

APPROXIMATE FLOW RATE ($\bar{Q}$) cfh	ORIFICE READING (ΔH) in. H_2O	CALIBRATION METER GAS VOLUME (V_{ds}) ft^3	METER BOX METER GAS VOLUME (V_d) ft^3	TEMPERATURE						METER BOX METER COEFFICIENT (Y_d)
				CALIBRATION METER			METER BOX METER			
				INLET (t_{dsi}) °F	OUTLET (t_{dso}) °F	AVERAGE ($\bar{t}_{ds}$) °F	INLET (t_{di}) °F	OUTLET (t_{do}) °F	AVERAGE ($\bar{t}_d$) °F	
									AVERAGE	

$$Y_d = Y_{ds} \frac{V_{ds}}{V_d} \cdot \frac{(\bar{t}_d + 460)}{[\bar{t}_{ds} + 460]} \cdot \frac{P_b}{[P_b + \frac{\Delta H}{13.6}]}$$

Figure 6. Example data sheet for calibration of meter box gas meter against a calibration dry gas meter (English units).

2. Rom, Jerome J. Maintenance, Calibration, and Operation of Isokinetic Source Sampling Equipment. Environmental Protection Agency, Research Triangle Park, N. C. APTD-0576. March, 1972.

3. Wortman, Martin, Robert Vollaro, and Peter Westlin. Dry-Gas Volume Meter Calibrations, Environmental Protection Agency monograph. Research Triangle Park, N. C. February, 1977.

DRY-GAS VOLUME METER CALIBRATIONS

By

Martin Wortman, Robert Vollaro and Peter Westlin[a]

INTRODUCTION

APTD 0576, "Maintenance, Calibration and Operation of Isokinetic Source-Sampling Equipment," specifies that the coefficients of dry-gas meters are to be determined by calibration against a direct-displacement wet test meter. This requirement can be burdensome to the tester, however, because the capital cost of wet test meters is high. The objective of these tests was to determine the feasibility of using a less expensive bellows dry-gas meter as a calibration standard. The experiments produced data sufficient to study the variation of the dry-gas meter coefficient (Y) with flow rate; and to determine the stability of Y over long periods of meter operation. This paper presents the results of these tests and discusses their significance.

TEST PROGRAM

The coefficient characteristics (i.e., variation of Y with flow rate and the operating stability of Y) of two dry-gas meters were investigated. At the outset, each dry-gas meter was calibrated against a spirometer. The calibration arrangement is shown in Figure 1a; each dry-gas meter was placed between the spirometer and a leakless, fiber vane pump, with the pump downstream. An orifice meter was placed downstream of the pump to measure the approximate gas flow rate, and a manometer was tapped between the spirometer and dry-gas meter to measure static pressure. Flow rate was controlled by a coarse control valve and a fine control bypass valve. The system was carefully leak-checked and any leaks were eliminated prior to calibration. The spirometer used in these tests was

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[a] Emission Measurement Branch, ESED, OAQPS, EPA, May, 1977.

manufactured by the Warren E. Collins Company[b]; it had a 600 liter capacity, and was a counter-balanced, frictionless device. Since the spirometer is a primary standard, its calibration coefficient was assumed to be 1.0 and independent of flow rate. During calibration runs, data were collected at five orifice settings in the range from 0.5 to 8.0 inches of water. The total volume of gas sampled was recorded at each orifice setting, for both the dry-gas meter and the spirometer; note that the sample volume was not the same at each setting, but was about 5 standard cubic feet (SCF) at orifice settings less than or equal to 1.0 in. H_2O, and about 10 SCF at the other orifice settings. In addition, the barometric pressure, static pressure of the dry-gas meter, temperature of both the spirometer and dry-gas meter, and the total sampling time were recorded at each orifice setting. The calibration procedure was completed twice at each setting.

Following their initial calibrations, the two dry-gas meters were connected in series downstream of the pump (Figure 1b); the flow rate was set at about 0.8 SCFM, and the system was allowed to run for about 16 hours. After the 16-hour test run, each dry-gas meter was returned to the calibration system (Figure 1a), leak-tested, and recalibrated, over the full range of orifice settings. The test run and recalibration sequence was repeated numerous times. The two meters were run for a combined total of 352 hours. Meter No. JA610713 operated for 192 hours, without adjustment. Meter No. JA610715 operated for 64 hours, at an average Y value of about 0.95; the meter cams were then reset, to produce a Y value closer to 1.0, and the meter was run for an additional 96 hours.

A wet test meter was also calibrated against the spirometer. The results of the wet test meter calibration are presented in the Appendix.

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[b] Mention of specific companies or products does not constitute endorsement by the Environmental Protection Agency.

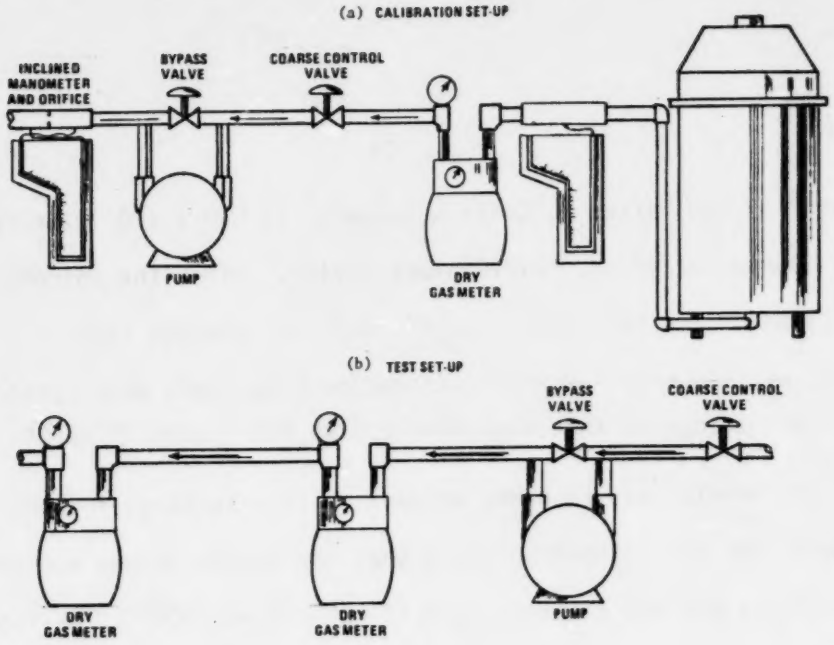

Figure 1. Equipment arrangement.

TABLE I. DRY-GAS VOLUME METER COEFFICIENT VALUES AT DIFFERENT ORIFICE SETTINGS

Total Hours of Operation	Dry-gas meter JA610715 calibration coefficients (Y)					
	0.5 in. H_2O	1.0 in. H_2O	2.0 in. H_2O	4.0 in. H_2O	6.0 in. H_2O	Average coefficient $\bar{Y}$
0	0.962	0.965	0.967	0.954	0.956	0.961
16	0.971	0.964	0.970	0.962	0.960	0.965
32	0.976	0.973	0.974	0.965	0.958	0.969
48	0.978	0.973	0.967	0.960	0.953	0.966
64	0.975	0.968	0.967	0.955	0.949	0.963

TABLE II. DRY-GAS VOLUME METER COEFFICIENT VALUES AT DIFFERENT ORIFICE SETTINGS

Total Hours of Operation	Dry-gas meter JA610715 calibration coefficients (Y)						
	0.5 in. H_2O	1.0 in. H_2O	2.0 in. H_2O	4.0 in. H_2O	6.0 in. H_2O	8.0 in. H_2O	Average coef. $\bar{Y}$
0	1.029	1.020	1.021	1.018	1.019	1.010	1.020
16	1.025	1.020	1.018	1.011	1.010	0.977	1.010
32	1.003	1.041	1.031	1.021	1.012	1.007	1.019
48	1.020	1.025	1.020	1.025	1.019	1.014	1.020
64	1.022	1.025	1.029	1.029	1.022	1.020	1.025
80	1.071	1.023	1.029	1.028	1.021	1.017	1.024
96	1.024	1.027	1.022	1.027	1.018	1.015	1.021

METHOD OF DATA ANALYSIS

The data from the experiments are presented in Tables I through III. A separate analysis was performed with the data listed in each of the three tables. These data were analyzed as outlined in (1) through (6) below.

(1) The dry-gas meter coefficient, Y (average of two determinations), was calculated at each orifice setting of each calibration run. The following equation was used:

$$Y = \frac{V_s \, P_b \, T_d}{V_d \left[P_b + \frac{P_d}{13.6} \right] T_s} \qquad \text{(Eq. 1)}$$

Where:

P_b = barometric pressure (in. Hg)

P_d = static gauge pressure in dry-gas meter (in. H_2O)

T_s = temperature of spirometer (^oR)

T_d = temperature of dry-gas meter (^oR)

V_s = sample volume measured by spirometer (SCF)

V_d = sample volume measured by dry-gas meter (SCF)

(2) The average dry-gas meter coefficient, $\overline{Y}$, was calculated for each calibration run, as follows:

$$\overline{Y} = \frac{\sum_{i=1}^{n} Y_i}{n} \qquad \text{(Eq. 2)}$$

Where:

Y_i = dry-gas meter coefficient values at the individual orifice settings

n = total number of orifice settings per run

TABLE III. DRY-GAS VOLUME METER COEFFICIENT VALUES AT DIFFERENT ORIFICE SETTINGS

Total hours of Operation	Dry-gas meter JA610713 calibration coefficients (Y)						
	0.5 in. H_2O	1.0 in. H_2O	2.0 in. H_2O	4.0 in. H_2O	6.0 in. H_2O	8.0 in. H_2O	Average coef. Y
0	1.019	1.013	1.013	1.010	0.993	-	1.010
16	1.005	1.018	1.012	1.002	0.992	-	1.006
32	1.018	1.017	1.016	1.007	0.997	-	1.011
48	1.011	1.012	1.004	0.991	0.983	0.971	1.000
64	1.015	1.002	0.999	0.991	0.986	0.976	0.995
80	1.017	1.013	1.012	1.003	0.992	0.987	1.000
96	1.009	1.007	1.012	1.008	1.005	1.000	1.007
112	1.008	1.006	1.015	0.999	1.005	0.993	1.004
128	1.000	1.008	1.015	1.005	0.996	1.000	1.004
144	1.020	1.020	1.011	1.006	1.000	0.999	1.009
160	0.998	1.013	1.014	1.008	1.003	0.999	1.006
176	1.002	0.999	1.013	1.015	1.005	0.997	1.005
192	1.000	1.009	1.003	1.001	0.993	1.000	1.001

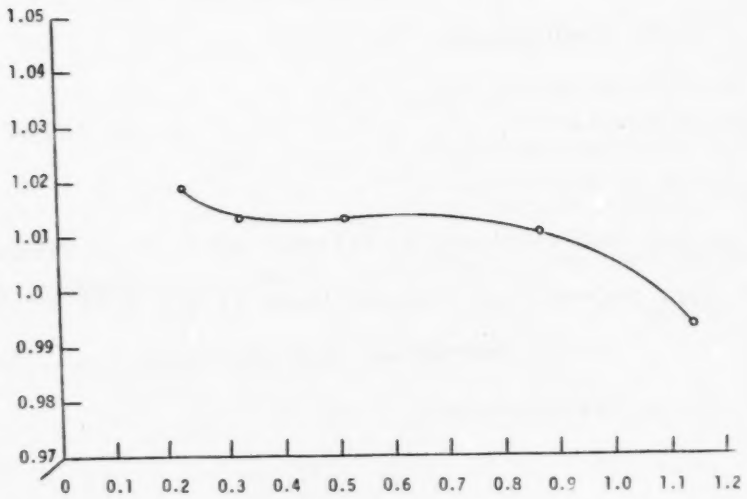

FIGURE 2. Typical Y Coefficient Versus Gas Flow Rate (Run Number 1, Meter JA610713)

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(3) The standard deviation from the average was calculated for each calibration run, using the following equation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - \overline{Y})^2}{n}} \qquad \text{(Eq. 3)}$$

(4) A plot of Y versus flow rate was constructed for each calibration run (e.g. Figure 2)

(5) A plot of $\overline{Y}$ versus total hours of meter operation (Figure 3) was constructed.

(6) A statistical analysis (analysis of variance) of the data was performed, to determine whether or not the observed variations in $\overline{Y}$ with operating time were statistically significant.

RESULTS OF DATA ANALYSIS

The results of the data analysis are presented in Figure 2 through 6, and in Table IV.

Figure 2 is a plot of Y versus flow rate, for a typical calibration run. Careful examination of 23 such curves showed that the variation of Y with flow rate is small for the range of flow rates tested. This range is consistent with the requirements of EPA Method 5. For Meter No. JA610715, the standard deviation (σ) values ranged from 0.004 to 0.021 and averaged 0.010 during the 96-hour calibration period; for the 64-hour period, σ ranged from 0.005 to 0.011, averaging 0.008. For Meter No. JA610713, the σ values ranged from 0.005 to 0.017, and averaged 0.009. The relationship between Y and flow rate appears to be characteristic

of the individual dry-gas meter. Different calibration curves were obtained for Meters JA610713 and JA610715; however, the general shape of the curves remained about the same for each meter from one calibration run to the next.

Figure 3 is a plot of $\overline{Y}$ versus hours of operation. Figure 3 shows that the value of $\overline{Y}$ changed very little with time; the changes that did occur seemed to be random in nature. For Meter No. JA610713, the percentage deviation between the highest and lowest values of $\overline{Y}$ (observed over 192 hours of operation) was only about 1 percent; for Meter No. JA610715, the percentage difference was about 1 percent during the 64-hour period and 1.5 percent during the 96-hour period.

The results of the statistical analysis are presented in Table IV. These results indicate that for the data shown in Tables I, II and III, the variation of $\overline{Y}$ with operating time is not statistically significant. This result is consistent with the plot of $\overline{Y}$ versus operating time shown in Figure 6.

CONCLUSIONS

Recent dry-gas meter calibration experiments have demonstrated the following:

(1) The dry-gas meter coefficient appears to be a function of flow rate. It appears to be charactersitic of the individual dry-gas meter. The variation of Y with flow rate is small (about 1 to 2 percent over the orifice setting range from 0.5 to 8.0 in. H_2O) and non-uniform.

(2) The value of the dry-gas meter coefficient is stable with respect to operating time. For operating times of up to 192 hours, the variation in $\overline{Y}$ was observed to be only about 1 percent, and was attributable to experimental error.

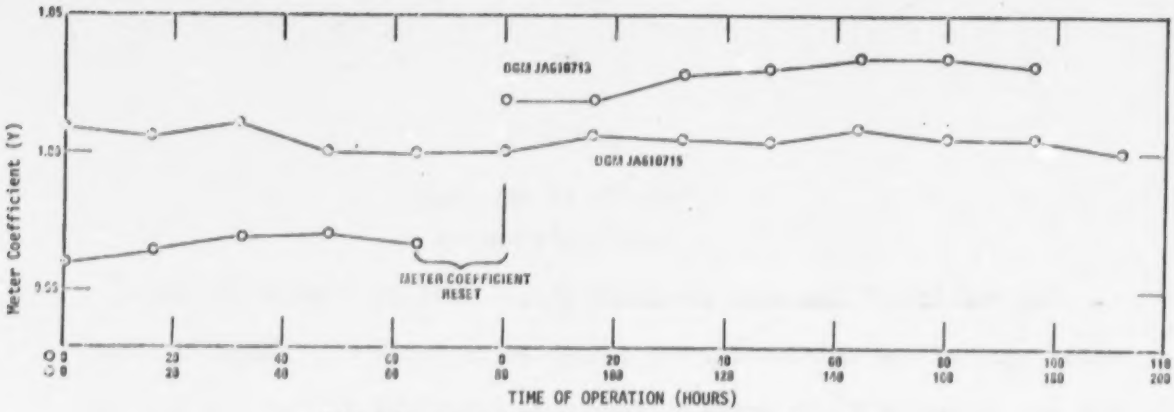

Figure 3 Dry gas meter correction coefficient average vs. hours of operation.

TABLE IV. Results of Statistical Analysis

Meter no.	Calculated F value	F-values from statistical table	
		0.01 level	0.05 level
JA610715 (64-hr. period)	0.805	4.43	2.87
JA610715 (96-hr. period)	1.73	3.37	2.37
JA610713 (192-hour period)	1.22	2.47	1.90

TABLE A1. Wet-Test Meter Calibration Coefficients Determined at Different Gas Flow Rates

Run no.	Value of Y at Flow Rate of:					
	0.22 cfm	0.32 cfm	0.51 cfm	0.87 cfm	1.14 cfm	1.39 cfm
1	1.0028	1.0025	1.0145	1.0040	0.9991	-
2	1.0083	1.0163	1.0183	1.0142	0.9978	0.9950
3	0.9995	1.0030	1.0017	0.9926	0.9897	0.9856
4	0.9943	0.9953	0.9964	0.9926	0.9854	0.9848
Average of Four Runs (Y*)	1.0012	1.0043	1.0078	1.0008	0.9930	0.9885
Percentage Deviation of Y* From 1.00	0.1%	0.4%	0.8%	0.1%	0.7%	1.1%

Avg. 0.5%

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APPENDIX

Results of Wet Test Meter Calibration

The results of the experiments in which a wet test meter was calibrated against the spirometer, are presented in Table A1. Table A1 shows that the values of Y^* (average of four determinations of Y at the individual flow rates) for the wet test meter ranged from 0.9885 to 1.0078. The percentage deviations of the Y^* values from unity (1.00) ranged from 0.1 to 1.1 percent, and averaged 0.5 percent. These results indicate that at flow rates ranging from 0.2 to 1.4 cfm, the coefficient of a wet test meter remains sufficiently close to unity to warrant use of the wet test meter as a primary standard for the calibration of reference dry-gas meters.

CALIBRATION OF DRY GAS METER AT LOW FLOW RATES

R. T. Shigehara and W. F. Roberts

INTRODUCTION

In a description of the moisture (Method 4) and sulfur dioxide (Method 6) gas-sampling methods, the December 23, 1971, Federal Register[1] specifies the use of a volume meter "sufficiently accurate to measure the sample volume within 1%." These gas-sampling trains were evaluated to determine (1) an acceptable calibration procedure and (2) the accuracy of the volume meters.

PROCEDURE

Test Equipment

The test train metering components used were the same as those specified by Method 6, except that the metering valve was placed before the pump, a small surge tank was placed between the pump and flow meter, and the silica gel drying tube was not used. This modified arrangement does not alter performance of the train.[2] The dry gas meter (0.1 ft^3/rev.) employed was a Rockwell Meter No. 175S;* discussion in this paper is, therefore, limited to this type of meter. A wet test meter (0.05 ft^3/rev.) was connected to the inlet of the metering system. A schematic of the calibration system is shown in Figure 1.

Test Procedure

The calibration was conducted in the following manner:

1. A leak check of the pump system was first conducted. This check consisted of connecting a vacuum gauge (mercury manometer) to the inlet of the metering system, turning on the pump, pinching off the line after the pump, turning off the pump after maximum vacuum was reached, and noting the gauge reading. If any leak was noted by a drop in gauge reading, it was corrected before proceeding

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* Mention of a specific company and model number does not signify endorsement by the Environmental Protection Agency.

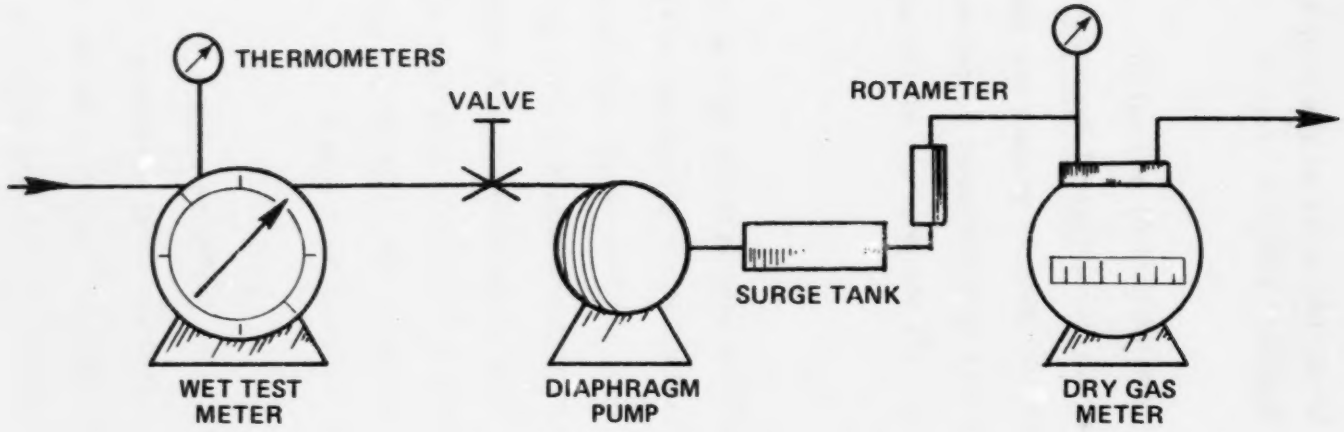

Figure 1. Test sampling train arrangement.

with the calibration run. (Note: In a Thomas Model No. 107CA20, leaks can occur within the pump where the diaphragm is connected by two screws to the connecting rod.)

2. Using the rotameter as a flow rate indicator, the following information was gathered: Rotameter readings (levels of 0.5, 1.0, 2.0, 4.0, 6.0, and 10.0 cfh), wet test meter volumes (running totals at increments of 0.1 ft^3) and temperatures, dry gas meter temperatures and volumes, corresponding to the wet test meter volumes and running time. Two runs were made at each level of rotameter readings. From the raw data, the calibration factor, which is the ratio of wet test meter volume to dry gas meter volume (both corrected for temperature and pressure differences) was computed.

RESULTS

The data (percent deviation vs. sample volume) for all test runs are plotted in Figure 2. The maximum percent deviations at a dry gas meter volume of 0.1 and 0.2 ft^3 are shown in Table I.

Table I. MAXIMUM DEVIATION AT DRY GAS METER VOLUME OF 0.1 AND 0.2 FT^3

Meter No.	Maximum deviation, percent	
	0.1 ft^3	0.2 ft^3
1	+2.5 -5.0	+2.3 -2.0
7	+5.5 -6.0	+3.0 -4.0
9	+7.9 -6.9	+3.3 -3.0
11	+4.6 -6.3	+3.2 -3.5

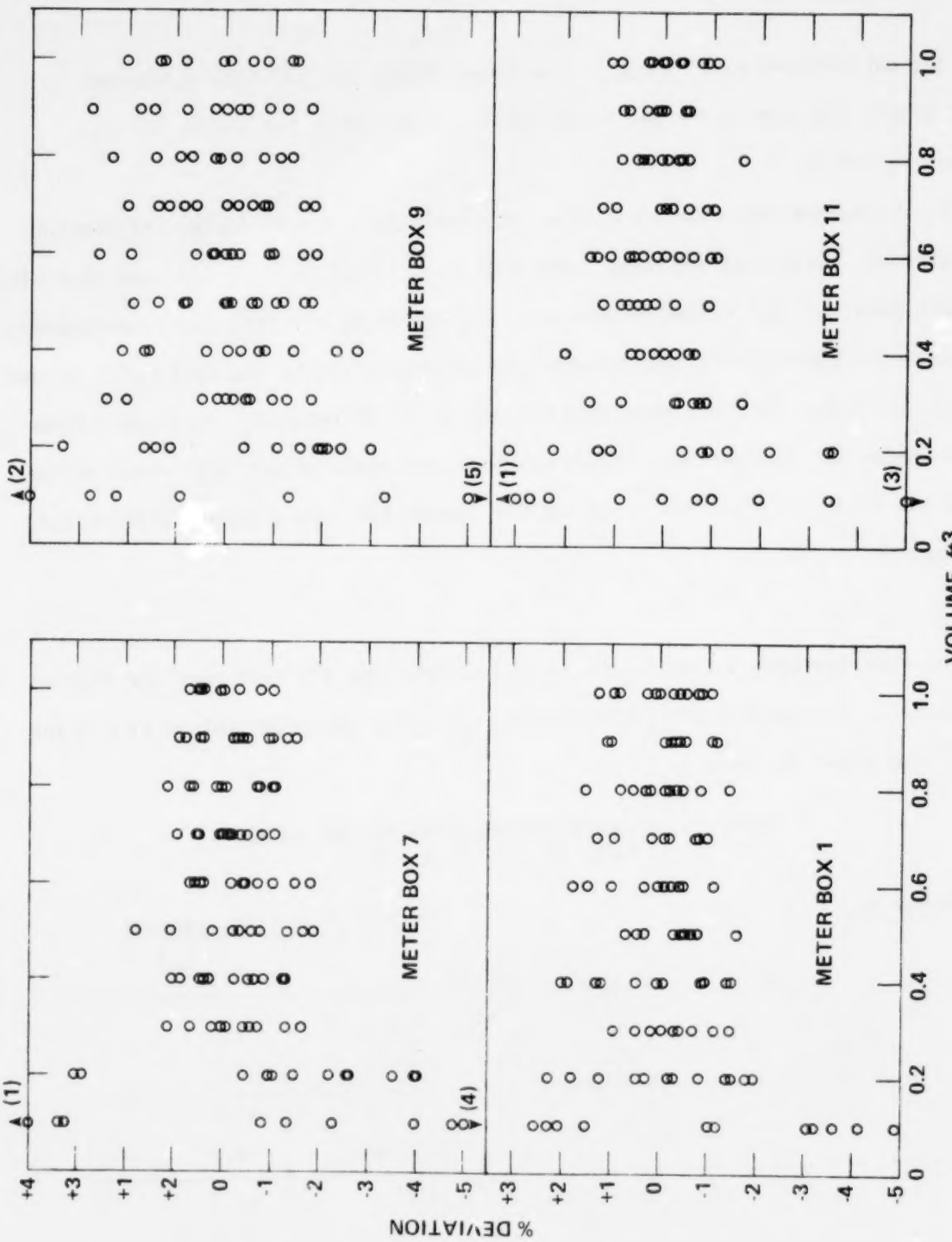

Figure 2. Percent deviation vs. volume.

It is apparent from the figure and the table that the volume used in the calibration procedure is definitely a factor in the calibration. Originally, it was assumed that 1 revolution on the dry gas meter would provide a reproducible measurement. The data show, however, that at least 3 revolutions or 0.3 ft^3 is necessary to provide a stable calibration factor within $\pm$ 2 percent.

In Figure 3, the percent deviation is plotted against the flow rate; the data corresponding to the volumes of 0.1 and 0.2 ft^3 are deleted. Figure 3 shows that the calibration factor is a function of flow rate. Because of the more pronounced effect of flow rate on Meter No. 9, the experiment was repeated and the resulting data are shown as Test 2 in Figure 3. An effect similar to the previous one was observed.

The dependency of the calibration factor on flow rate shows that best accuracy is obtained if calibration factors are determined at individual flow rates. This observation is not unreasonable as most gas sampling tests involve sampling at one flow rate or, if proportional sampling is conducted, at rates varying by no more than a factor of 2. To determine the variation of the calibration at one flow rate, 10 runs were made at a flow rate of 2 cfh, with readings taken at volumes of 0.3, 0.4, 0.5 ft^3. The results are shown in Figure 4. This experiment shows that three of the meters are not capable of operating within $\pm$ 1 percent of the wet test meter readings; a $\pm$ 2 percent deviation is more reasonable.

CALIBRATION PROCEDURE

On the basis of the results of the experiments previously discussed, the following calibration procedure is suggested.

1. Leak check the sampling train as described under Test Procedure.

2. Calibrate the dry gas meter at the desired flow rate (as specified by the test methods).

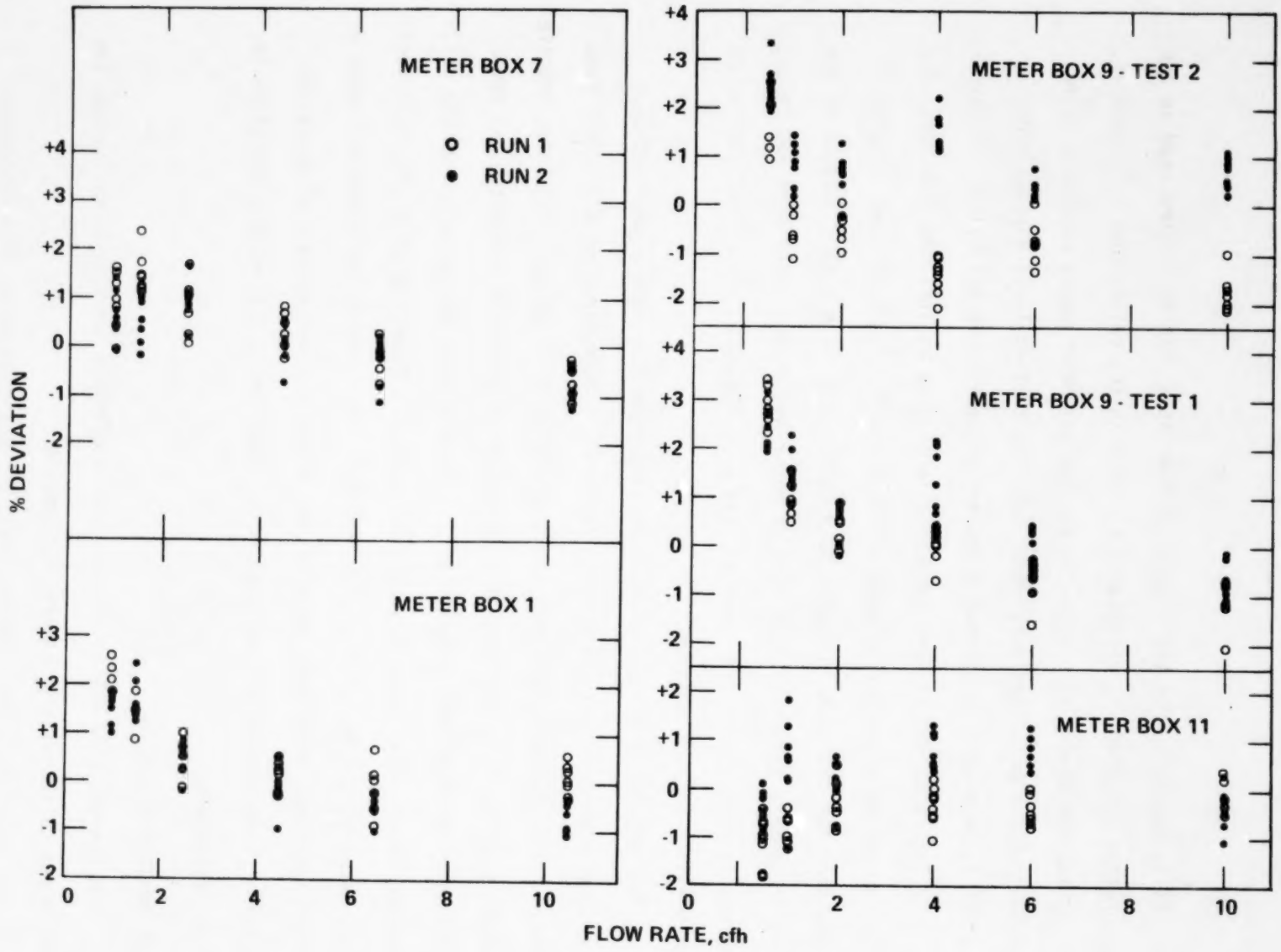

Figure 3. Percent deviation vs. flow rate.

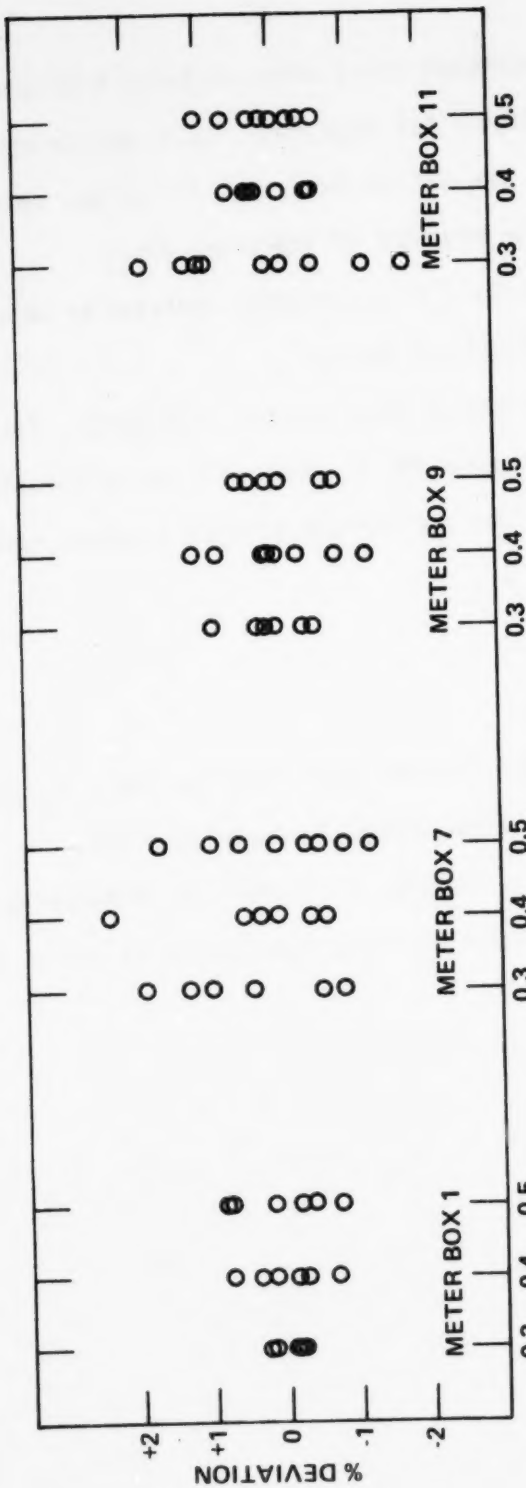

Figure 4. Percent deviation vs. volume at 2 cfh.

3. Make three independent runs, using at least 5 revolutions, and calculate the calibration factor for each run. The 5 revolutions were selected over 3 and 4 to minimize the estimation errors in dry gas meter readings and to allow for the irregular movement of the meter dial.

4. Average the results. If any reading deviates by more than $\pm$ 2 percent from the average, reject the meter.

5. Make periodic checks of meter (after each test). For these checks, 0.3 ft^3 (3 revolutions) or more may be used. If the calibration factor deviates by more than $\pm$ 2 percent from the average of Step 4 above, recalibrate the dry gas meter as in Steps 1 - 4.

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1. Standards of Performance for New Stationary Sources. Federal Register (Washington) 36 (247): 24882-24895, December 23, 1971.

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CALIBRATION OF PROBE NOZZLE DIAMETER

P. R. Westlin and R. T. Shigehara*

Introduction

Document APTD-0576, Maintenance, Calibration, and Operation of Isokinetic Source-Sampling Equipment,[1] requires that the diameter of the probe nozzle opening for source sampling be calibrated with a micrometer to the nearest 0.001 inch. According to the document, 10 different diameters should be measured and the average of the readings used as the nozzle diameter. To ensure roundness, it is specified that the largest deviation from the average must not exceed 0.002 inch.

The requirement for 10 measurements has been questioned. It has been suggested, instead, that 3 measurements would be practical and adequate for accurate nozzle-diameter measurements. To examine this possibility, a short study was conducted to determine if reasonable accuracy could be obtained from 3 nozzle diameter measurements.

Test Program

Five differently sized nozzles were chosen for this study. The nozzle tips were visually inspected for dents and roundness, corrosion, and nicks. If the nozzles were not in good general condition, they were rehoned and reshaped.

Two technicians were assigned to make 10 measurements of each nozzle diameter as outlined by the procedure in APTD-0576, except measurements were made to the nearest 0.0001 inch. Internal calipers were used to gauge the diameters. The same technicians then made three additional measurements of

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the nozzles' diameters following the same technique.

Results and Discussion

The collected data are shown in Table 1. A first analysis of the data involved a simple comparision of the averages obtained by the two technicians. First, when comparing the measurements of technician A to those of technician B, no pair of average readings for the two technicians varied by more than 0.001 inch when rounded to the nearest 0.001 inch. This was true for the averages of 3 measurements as well as for the averages of 10 measurements. The maximum deviation from the average for either technician exceeded 0.002 inch in only one case, and this value was less than 0.003 inch.

In the second comparison, it was found that the averages of the 10 readings differed from the averages of 3 readings by no more than 0.001 inch when rounded to the nearest 0.001 inch. The maximum deviations from the average tended to the smaller for the 3 reading averages than for the 10 reading averages.

An error or bias in the diameter of a sampling nozzle is more significant for smaller nozzles than for larger nozzles. An error of 0.001 inch in the measurement of the diameter of a 0.125-inch diameter nozzle will introduce an error of about 1.6 percent in the isokinetic rate adjustments[2,3]. For most applications, this is an acceptable error.

In a third analysis of the data, the statistical t-test was used, to determine if the average of the 3 readings of the nozzle diameter for each

TABLE 1

Nozzle Diameter Measurements

(in.)

Nozzle Number	1		2		3		4		5	
Reading	Technician A	Technician B	A	B	A	B	A	B	A	B
1	0.1536	0.1536	0.2511	0.2515	0.3136	0.3138	0.3762	0.3779	0.5014	0.4977
2	0.1536	0.1536	0.2501	0.2510	0.3141	0.3141	0.3767	0.3769	0.5002	0.5008
3	0.1533	0.1537	0.2511	0.2522	0.3139	0.3144	0.3762	0.3770	0.4999	0.4966
4	0.1554	0.1530	0.2508	0.2518	0.3139	0.3144	0.3766	0.3770	0.4992	0.5001
5	0.1544	0.1528	0.2496	0.2510	0.3142	0.3147	0.3770	0.3771	0.4980	0.5000
6	0.1536	0.1533	0.2508	0.2512	0.3138	0.3137	0.3759	0.3767	0.5003	0.4986
7	0.1556	0.1526	0.2501	0.2505	0.3140	0.3144	0.3781	0.3774	0.4995	0.5017
8	0.1551	0.1523	0.2508	0.2517	0.3134	0.3137	0.3763	0.3765	0.5007	0.4982
9	0.1541	0.1531	0.2510	0.2517	0.3141	0.3141	0.3768	0.3781	0.4996	0.5000
10	0.1547	0.1520	0.2512	0.2519	0.3143	0.3142	0.3763	0.3771	0.5015	0.4999
Average	0.1543	0.1530	0.2507	0.2514	0.3139	0.3142	0.3766	0.3772	0.5000	0.4994
Maximum Deviation	0.0013	0.0010	0.0011	0.0009	0.0005	0.0005	0.0015	0.0009	0.0020	0.0028
11	0.1530	0.1533	0.2504	0.2501	0.3144	0.3140	0.3774	0.3777	0.4991	0.5015
12	0.1532	0.1536	0.2511	0.2518	0.3143	0.3141	0.3780	0.3771	0.4984	0.5003
13	0.1527	0.1536	0.2515	0.2516	0.3142	0.3139	0.3771	0.3766	0.5011	0.4993
Average	0.1530	0.1535	0.2510	0.2512	0.3143	0.3140	0.3775	0.3771	0.4995	0.5004
Maximum Deviation	0.0003	0.0002	0.0006	0.0011	0.0001	0.0001	0.0005	0.0006	0.0016	0.0011

technician was statistically different from average of the 10 readings. The results for technician A were different from those for technician B. Statistically significant differences were found between the two values for nozzle 1 and 4 for this technician. The result indicates a possible bias between the two sets of readings, but, as noted previously, the actual magnitude of the bias is small. For technician B, no significant differences were found between any of the averages.

Summary

It has been found that visual inspection is sufficient to determine roundness of nozzles. For well-honed nozzles, averaging 3 diameter readings instead of 10 readings introduces only a small error in the diameter value and is sufficiently accurate for stack sampling work. To ensure roundness and to prevent gross errors in measurements of the nozzle tip, however, it is recommended that the range of diameter readings not exceed 0.004 inch.

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LEAK TESTS FOR FLEXIBLE BAGS

F. C. Biddy and R. T. Shigehara*

INTRODUCTION

"Method 3 - Gas Analysis for Carbon Dioxide, Excess Air, and Dry Molecular Weight", published in the December 23, 1971, Federal Register,[1] specifies that the flexible bag used in the integrated gas-sampling train be leak-tested in the laboratory before use. A procedure for leak testing is not given, however. Therefore, several methods were considered and investigated. On the basis of this investigation, leak test procedures are recommended for laboratory and field uses.

TESTING METHODS

Some commonly used leak test methods for flexible bags are as follows:

1. Evacuating the bag to about 25 in. Hg vacuum. Leaks are indicated by movement of the vacuum gauge indicator, which is left attached. Experience has shown that this method does not detect leaks at times, because of the bag film plugging the valve outlet. There are also indications that bag life is shortened because of the additional number of times the bag is evacuated. Therefore, this method was dropped from further consideration.

2. Inflating the bag and submerging it in water. Leaks are detected by air bubbles. This method is very effective in locating leaks. However, considerable pressure must be exerted on the bag when submerged to locate tiny leaks, and the bag can only be tested when separated from its protective container.

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3. Inflating the bag to low positive pressure (2-4 in. H_2O), sealing it, and allowing it to stand overnight. A visible collapse of the bag indicates a leak. Except for the time element, this method is very effective for determining leaks.

4. Inflating the bag to a low positive pressure (2-4 in. H_2O) and connecting bag to a water manometer. A drop in pressure denotes a leak. This method is quite sensitive for detecting leaks and can be used in a short period of time.

RECOMMENDED LEAK CHECK PROCEDURE

On the basis of an investigation of the various testing methods, the following leak-test procedures are recommended for laboratory and field uses:

1. After the bag is manufactured or upon receipt of the bag from a distributor, leak-test the bag by either one of the following two methods:

Method A. Inflate the bag to a positive pressure of about 2-4 in. H_2O, connect the bag to a water manometer, and observe the pressure for an interval of 10 minutes. If any visible drop occurs, repair or discard the bag. Temperature changes will affect the reading on the manometer. With a leakless bag, the reading should stabilize within 5 minutes.

Method B. As an alternative method for leak checking a bag in the laboratory, inflate the bag to a positive pressure of about 2-4 in. H_2O, seal it, and allow it to set overnight. If any visible collapsing of the bag occurs, repair or discard the bag.

2. Using bags that pass the above leak test, place the bag in a rigid container (with a vent) to prevent puncture when in the field. Then, leak

check the bag, using Method A.

3. In the field, just prior to sampling, conduct the leak test, using Method A.

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ADJUSTMENTS IN THE EPA NOMOGRAPH FOR DIFFERENT PITOT TUBE COEFFICIENTS AND DRY MOLECULAR WEIGHTS

R. T. Shigehara*

INTRODUCTION

In order to sample isokinetically, the flow rate through the sampling train nozzle must be such that its corresponding velocity at the nozzle tip is equal to that of the measuring point within the stack. For a sampling train utilizing a calibrated pitot tube and a calibrated orifice meter, this is done by setting the pressure differential (ΔH) across the orifice to the value that corresponds isokinetically to the velocity head (Δp) as determined by the pitot tube in the stack.

Nomographs have become useful tools for determining the proper ΔH's for rapid isokinetic sampling rate adjustments. One such nomograph is the Environmental Protection Agency Method 5 nomograph,[1,2] which is now widely used and is also commercially available.

Certain assumptions have been made in the construction of the EPA nomograph. In particular, the pitot tube is assumed to have a coefficient of 0.85 and the dry molecular weight of the stack gas is assumed to be 29. The purpose of this paper is to show how adjustments in nomograph values can be made to account for differences in pitot tube coefficients and in dry molecular weights. In addition, steps are given for checking the accuracy of commercially available nomographs.

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NOMENCLATURE

B_{wm} = water vapor in sample gas at meter, proportion by volume

B_{ws} = water vapor in stack gas, proportion by volume

C = ratio of $K_{act}/K_{@}$, dimensionless

C_{adj} = adjusted C value, dimensionless

C_p = pitot tube coefficient, dimensionless

D_n = nozzle diameter, in.

ΔH = orifice meter pressure differential, in. H_2O

$\Delta H_{@}$ = ΔH that gives 0.75 ft^3/min dry air at 70°F and 29.92 in. Hg

ΔH_{act} = actual ΔH read from nomograph scale

$$K_{act} = \frac{60^2 \, K_p^{\,2} \, C_p^{\,2} \, \pi^2 \, \Delta H_{@} \, T_m \, P_s}{0.921 \, [(4)(144)]^2 \, P_m} \left[\frac{M_d \, (1 - B_{ws})^2}{M_d \, (1 - B_{ws}) + 18 \, B_{ws}} \right]$$

$K_{@}$ = 5.507 x 10^5, calculated from K_{act} assuming that C_p = 0.85; T_m = 530°R (70°F); $\Delta H_{@}$ = 1.84 in. H_2O; $P_s = P_m$ = 29.92 in. Hg; M_d = 29 lb_m/lb_m - mile; and B_{ws} = 0.05 (lb_m = pound mass)

K_m = orifice meter constant, $\frac{ft^3}{min} \left[\frac{(\text{in. Hg}) \, (lb_m/lb_m - \text{mole})}{(°R) \, (\text{in. } H_2O} \right]^{1/2}$

K_p = pitot tube constant, 85.48 $\frac{ft}{sec} \left[\frac{(\text{in. Hg}) \, (lb_m/lb_m - \text{mole})}{(°R) \, (\text{in. } H_2O)} \right]^{1/2}$

$M_{@}$ = dry molecular weight of air of 29 lb_m/lb_m - mole

M_d = dry molecular weight of stack or sample gas, lb_m/lb_m - mole

M_m = molecular weight of sample gas at meter, lb_m/lb_m - mole

M_s = molecular weight of stack gas, lb_m/lb_m - mole

Δp = velocity head of stack gas, in. H_2O

$P_@$ = absolute orifice meter pressure of 29.92 in. Hg

P_m = absolute meter pressure, in. Hg

P_s = absolute stack gas pressure, in. Hg

$Q_@$ = orifice meter flow rate of 0.75 ft^3/min of dry air at 70°F and 29.92 in. Hg

$T_@$ = absolute orifice meter temperature of 530°R

T_m = absolute stack gas temperature, °R

t_m = meter temperature, °F

t_s = stack gas temperature, °F

$Y = (M_s/M_m)\ [(1 - B_{ws})/(1 - B_{wm})]^2$

18 = molecular weight of water, lb_m/lb_m - mole

29 = molecular weight of dry air, lb_m/lb_m - mole

60 = conversion factor, sec/min

144 = conversion factor, $in.^2/ft^2$

BASIC EQUATIONS

Isokinetic Equation

The basic isokinetic equation that relates the pitot tube velocity head reading (Δp) to the orifice meter pressure differential reading (ΔH) is:

$$\Delta H = \frac{60^2 K_p^2 C_p^2 \pi^2 D_n^4 P_s T_m M_m}{K_m^2 [(4)(144)]^2 P_m T_s M_s} \left[\frac{1 - B_{ws}}{1 - B_{wm}}\right]^2 \Delta p \qquad (1)$$

Definition of $\Delta H_@$

The EPA nomograph equation modifies Equation 1 by defining the orifice meter constant K_m in terms of a value called "$\Delta H_@$," which is a ΔH value measured for a given orifice operating under specifically selected conditions. These selected conditions, based on general sampling conditions and sampling train design, are a flow rate of 0.75 ft^3/min of dry air at 70°F and 29.92 in. Hg. In practice, the orifice meter is first calibrated and K_m calculated. Then $\Delta H_@$ is determined by the following equation:

$$\Delta H_@ = \frac{Q_@^2 P_@ M_@}{K_m^2 T_@} = \frac{0.921}{K_m^2} \qquad (2)$$

Molecular Weight and Moisture

Equation 1 assumes that changes in molecular weights are due only to water in the stack gas. Since M_s and M_m are functions of B_{ws} and B_{wm}, respectively, the term $(M_s/M_m)[(1 - B_{ws})/(1 - B_{wm})]^2$, which will be defined as "Y," can be written as:

$$Y = \left[\frac{M_d (1 - B_{wm}) + 18 B_{wm}}{M_d (1 - B_{ws}) + 18 B_{ws}}\right] \left[\frac{1 - B_{ws}}{1 - B_{wm}}\right]^2 \qquad (3)$$

In the EPA sampling train, silica gel is used to dry the sample gas stream, so it is assumed that B_{wm} is zero. Thus, Equation 3 becomes:

$$Y = \frac{M_d\ (1 - B_{ws})^2}{M_d\ (1 - B_{ws}) + 18\ B_{ws}} \tag{4}$$

EPA Isokinetic Equation

Substituting Equations 2 and 4 into Equation 1, the EPA isokinetic equation is obtained:

$$\Delta H = \frac{60^2\ K_p^{\ 2}\ C_p^{\ 2}\ \pi^2\ D_n^{\ 4}\ P_s\ T_m}{\frac{0.921}{\Delta H_@}\ [(4)\ (144)]^2\ P_m\ T_s} \left[\frac{M_d\ (1 - B_{ws})^2}{M_d\ (1 - B_{ws}) + 18\ B_{ws}}\right] \Delta p \tag{5}$$

In practice, the calculation of Equation 5 is carried out by two nomographs. These are the Operating Nomograph and the Correction Factor for C Nomograph.

EPA Operating Nomograph Equation

The Operation Nomograph equation is obtained by rewriting Equation 5 as:

$$\Delta H = K_@\ C\ \frac{D_n^{\ 4}}{T_s}\ \Delta p \tag{6}$$

EPA Correction Factor for C Nomograph Equation

The factor C in Equation 6 is usually a constant during sampling at a given site, but it may change for different sampling locations or processes. The Correction Factor for C Nomograph is designed to account for changes in $\Delta H_@$, T_m, P_m, P_s, and B_{ws}. C_p and M_d are still assumed to remain as 0.85 and 29, respectively. Thus, this nomograph equation is represented by:

$$C = \frac{\Delta H_{@}\ T_m \frac{P_s}{P_m} - \frac{29\ (1 - B_{ws})^2}{29\ (1 - B_{ws}) + 18\ B_{ws}}}{897.1} \qquad (7)$$

ADJUSTING C FOR CHANGES IN C_p

The operations manual[3] for the EPA sampling train limits the selection of pitot tubes to those that have a coefficient (C_p) of 0.85 $\pm$ 0.02. However, this limitation is not necessary if C can be adjusted to account for the differences in C_p's. Realizing that C is also the ratio of $K_{act}/K_{@}$, it can be adjusted for differences in C_p's by the following equation:

$$C_{adj(C_p)} = C\ \frac{C_p^{\,2}}{0.85^2} \qquad (8)$$

The steps for adjusting C for differences in C_p's are as follows:

1. Determine C from the existing Correction Factor for C Nomograph by the usual manipulations. Example: For $\Delta H_{@}$ = 2.1 in. H_2O, t_m = 100°F, B_{ws} = 0.10 and P_s/P_m = 1.0, C equals 1.10.

2. Multiply C obtained from step 1 by the ratio of the squares of C_p's as shown in Equation 8 to obtain the adjusted C. Example: If C_p = 1.0, then:

$$C_{adj(C_p)} = 1.10\ \frac{1.0^2}{0.85^2} = 1.52$$

3. Set the adjusted value on the Correction Factor C scale (Example: $C_{adj(C_p)} = 1.52$) on the Operating Nomograph.

The following may be used as a guide to determine when adjustments in C_p's should be made. Each percent difference from 0.85 will introduce about 1 percent error in the isokinetic rate. Generally, about 5 percent error is tolerable. Thus, when $0.87 \leq C_p \leq 0.83$, or when $0.95 \leq C_p^2/0.85^2 \leq 1.05$, adjustments should not be necessary.

ADJUSTING C FOR CHANGES IN M_d

Adjustments for differences in M_d's can be effected by the following equation:

$$C_{adj(M_d)} = C \frac{(1 - B_{ws}) + 18 B_{ws}/29}{(1 - B_{ws}) + 18 B_{ws}/M_d} \qquad (9)$$

In most sampling situations, where air and/or combustion products of fossil fuels are the principle constituents of the stack gas stream, the amount of adjustment is quite minimal (see Table I) and adjustments are not necessary. However, for stack gases consisting primarily of lower molecular weight gases, e.g. hydrogen, adjustments become significant and must be made. In addition, the orifice meter will need to be redesigned, and the Operating Nomograph C-scale may need to be modified by extending the logarithmetic scale.

Table I shows the adjustment factor, $\frac{(1 - B_{ws}) + 18 B_{ws}/29}{(1 - B_{ws}) + 18 B_{ws}/M_d}$, for some selected values of M_d's and B_{ws}'s.

TABLE I. ADJUSTMENT FACTORS FOR SELECTED M_d's AND B_{ws}'s

B_{ws}	M_d					
	2	20	25	28	30	31
0	1.00	1.00	1.00	1.00	1.00	1.00
0.05	0.70	0.99	0.99	1.00	1.00	1.00
0.10	0.53	0.97	0.99	1.00	1.00	1.00
0.15	0.43	0.96	0.98	1.00	1.00	1.01
0.20	0.36	0.94	0.98	1.00	1.00	1.01
0.25	0.30	0.93	0.97	0.99	1.01	1.01
0.30	0.26	0.91	0.97	0.99	1.01	1.01
0.35	0.23	0.90	0.96	0.99	1.01	1.02
0.40	0.20	0.88	0.96	0.99	1.01	1.02
0.45	0.18	0.87	0.95	0.99	1.01	1.02
0.50	0.16	0.85	0.94	0.99	1.01	1.03

As a general rule, adjustments are not necessary when the adjustment factor is between 0.90 and 1.10 as each percent difference from 1.00 will introduce about 0.5 percent error. Beyond the above range, C should be adjusted in the following manner:

1. Determine C from the Correction Factor for C Nomograph by the usual manipulations.
2. Multiply C obtained in step 1 by the adjustment factor as shown in Equation 9 to obtain $C_{adj(M_d)}$.
3. Set $C_{adj(M_d)}$ on the Correction Factor C-scale of the Operating Nomograph.

ACCURACY OF NOMOGRAPHS

When calculations for isokineticity show consistent departure from 100 percent of isokinetic conditions, one cause might be the inaccuracy of the nomograph. The steps below may be used to check the accuracy of nomographs.

Overall Accuracy

Errors in the Operating Nomograph and Correction Factor for C Nomograph may be offsetting or additive. To check the sum total effect, Equation 5 should be used. Arbitrarily select values for the variables and calculate the corresponding ΔH's. Examples are given in Table II. For each percent difference, there will be about 0.5 percent error in adjusting the isokinetic flow rate.

TABLE II. CALCULATED ΔH's FOR SELECTED VALUES

$\Delta H_@$		$100B_{ws}$	P_s/P_m	C	D_n	t_s	Δp	ΔH	ΔH_{act}	%Diff.
1.84	70	5	1.00	1.00	0.30	1000	1.0	3.06		
3.00	0	30	0.90	0.765	0.25	500	2.0	3.43		
3.00	0	50	1.20	0.569	0.20	200	2.0	1.52		
2.30	140	0	1.10	1.69	0.40	1500	0.7	8.51		
1.00	140	10	1.00	0.563	0.25	300	2.0	4.33		
1.20	40	20	1.20	0.556	0.20	200	1.0	0.74		
2.00	100	30	1.20	0.828	0.25	500	2.0	3.71		

Generally, about 10 to 15 percent differences will yield sampling rates within 10 percent of isokinetic. If greater differences are encountered, the

separate nomographs may be checked as follows:

Operating Nomograph

K-Factor Line and ΔH and Δp Scales. The accuracy of the placement of the K-Factor line and the ΔH and Δp scales may be checked in the manner shown in Table III. Deviations of 10 percent from the true ΔH values are generally acceptable.

Table III. K-FACTOR LINE AND ΔH AND Δp SCALES CHECK

Set Pivot Point after Aligning:	Set Δp to:	ΔH Should Read:
$\Delta p = 0.001$; $\Delta H = 0.1$	0.01 0.1	1.0 10
$\Delta p = 10$; $\Delta H = 10$	1.0 0.1	1.0 0.1
$\Delta p = 0.1$; $\Delta H = 1.0$	1.0 0.01	10 0.1

C, t_s, and D_n Scales. To check the C, t_s, and D_n scales, arbitrarily select values for the variables in Equation 6 and calculate ΔH's. Nomograph manipulations should yield values corresponding to the calculated values of ΔH's. Examples are given in Table IV. As a general rule, a 10 percent deviation may be tolerated without appreciable errors. However, it should be realized that the inaccuracies here, which include the inaccuracies from the placement of the K-Factor line and the ΔH and Δp scales, may be offset or compounded by inaccuracies in the Correction Factor for C Nomograph.

Table IV. CALCULATED ΔH's FOR SELECTED VALUES

C	D_n	t_s (°F)	Δp	ΔH
2.0	0.5	2500	0.2	4.65
1.5	0.4	1500	0.7	7.55
1.0	0.3	1000	1.0	3.06
0.7	0.25	500	2.0	3.14
0.5	0.2	200	1.0	0.668

Correction Factor for C Nomograph

To check the accuracy of the Correction Factor for C Nomograph, arbitrarily select values for the variables in Equation 7 and calculate the corresponding C's. As a general rule, the nomograph manipulations should yield, to within 10 percent, the same values of C's. The example calculations in Table II may be used for this purpose.

SUMMARY

Equations and steps have been given that show how the factor C of the EPA Method 5 Monograph can be adjusted to account for values of (C_p) the pitot tube coefficient and dry molecular weight of the sample gas (M_d) different from 0.85 and 29, respectively. In addition, directions and tables have been presented for checking the accuracy of commercially available nomographs.

ACKNOWLEDGEMENT

The author wishes to thank Mr. Walter S. Smith of Entropy Evironmentalists, Inc., Research Triangle Park, North Carolina, for his assistance in writing this paper.

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3. Rom, J.J. Maintenance, Calibration, and Operation of Isokinetic Source-sampling Equipment. U.S. Environmental Protection Agency. Research Triangle Park, N.C. Publication No. APTD-0476. March 1972.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

SUBJECT Expansion of EPA Nomograph DATE MAY 21 1974

FROM R. T. Shigehara, TSS, EMB RS

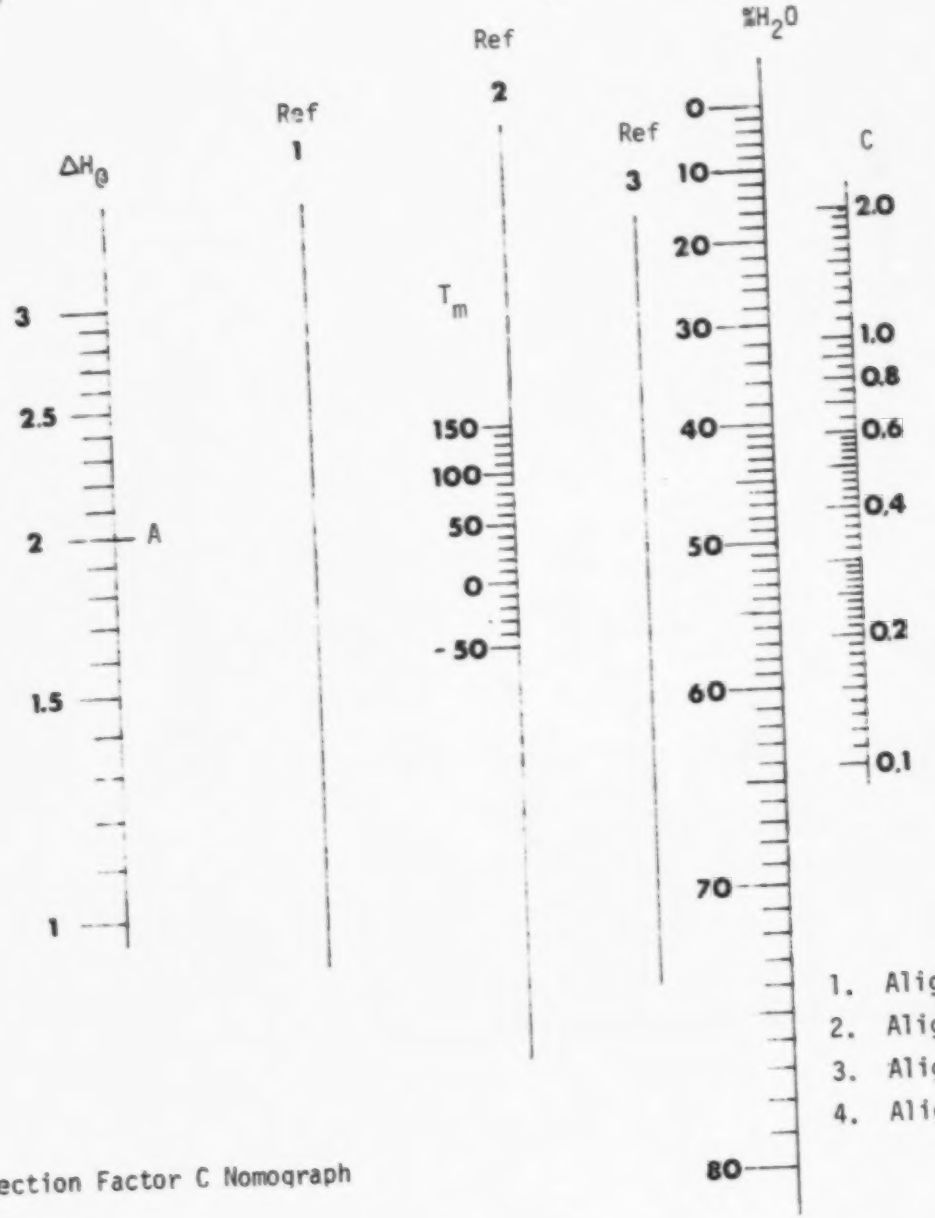
TO Emission Measurement Branch Personnel

Enclosed is a copy of the expanded EPA nomograph for determining the Correction Factor C for high moisture contents. Directions are on the nomograph.

Directions on how to expand the C-scale on the Operating Nomograph are also enclosed.

Should you have any questions, please contact me.

Enclosure

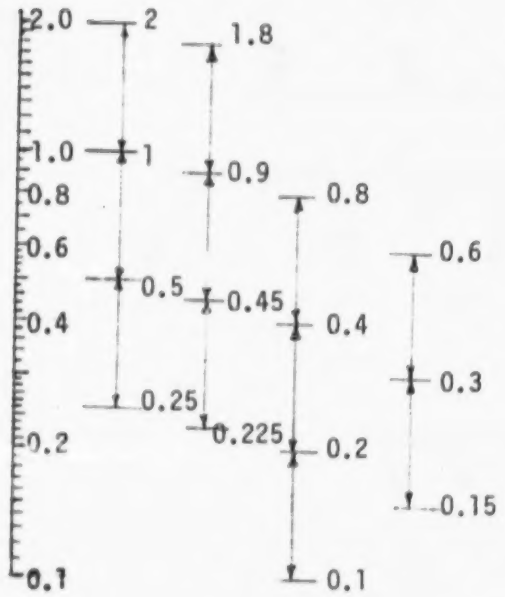


1. Align $\Delta H_@$ with T_m to obtain Ref 1.
2. Align Ref 1 with $\%H_2O$ to obtain Ref 2.
3. Align Ref 2 with P_s/P_m to obtain Ref 3.
4. Align Ref 3 with A on $\Delta H_@$ scale to obtain C.

Correction Factor C Nomograph

Expanding Logarithmic Scales

1. Determine the distance between 2.0 and 1.0. This distance should be the same as between 1.0 and 0.5, since the ratio is 2.
2. Obtain other points by using this ratio and distance obtained from (1). This is illustrated below.



All distances shown are equal.

etc.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

SUBJECT: EPA Nomograph Adjustments

DATE: MAY 16 1974

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TO: Emission Measurement Branch Personnel

In a recent source test, high moisture content and high dry molecular weight effluent gases were encountered. Since the Environmental Protection Agency nomograph has a moisture scale range of only 0-50% and assumes a dry molecular weight of 29, adjustments to the EPA nomograph are necessary.

Attempts have been made to expand the % H_2O and the Correction Factor C scales. However, due to the magnitude of expansion, slight inaccuracies in the present nomograph are magnified. Thus, an entirely new nomograph for the Correction Factor C must be constructed.

Since the construction of the nomograph will take some time, the attached procedure is recommended for the interim. To handle the calculations, it is suggested that you use electronic pocket calculators.

Should you have any questions, please contact me.

Enclosure

MAY 16 1974

DIRECTIONS FOR SETTING EPA NOMOGRAPH

1. Obtain the following information:

Item	Dimensions
a. Orifice meter coefficient, $\Delta H_@$	in. H_2O
b. Pitot tube coefficient, C_p	dimensionless
c. Abs. stack pressure, $P_s = P_{bar} + P_g$	in. Hg
d. Abs. meter pressure, $P_m = P_{bar}$	in. Hg
e. Abs. meter temperature, $T_m = t_m + 460$	°R
f. Abs. stack temperature, $T_s = t_s + 460$	°R
g. Dry molecular weight, M_d	lb/lb-mole
h. Moisture content, $B_{ws} = \%H_2O/100$	dimensionless
i. Exact nozzle diameter, D_n	in.
j. Average velocity head, Δp	in H_2O

2. Calculate ΔH using the following equation:

$$\Delta H = 849.6\ C_p^{\,2}\ \Delta H_@\ \frac{P_s}{P_m}\ \frac{T_m}{T_s}\ \frac{M_d\ (1 - B_{ws})^2}{M_d\ (1 - B_{ws}) + 18\ B_{ws}}\ D_n^{\,4}\ \Delta p$$

This equation may be used to account for differences in C_p's, M_d's, $\%H_2O$, and/or any other variable within the equation.

3. Align calculated ΔH with average Δp on operating nomograph and set K-Factor pivot point.

GRAPHICAL TECHNIQUE FOR SETTING PROPORTIONAL SAMPLING FLOW RATES

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INTRODUCTION

The December 23, 1971, Federal Register[1] requires in certain test methods that the gaseous sample from an effluent gas stream be extracted in a proportional manner. "Proportional sampling," according to the Federal Register, means "sampling at a rate that produces a constant ratio of sampling rate to stack gas flow rate." In other words, the ratio (k) of the gas velocity (v_n) at the tip of the probe nozzle to the velocity (v_s) of the approaching gas stream at a measuring point within the stack cross section must remain a constant throughout the sampling period. In equation form:

$$\frac{v_n}{v_s} = k \qquad (1)$$

Since the velocities v_n and v_s are not directly measurable, the normal procedure is to regulate the sampling train meter flow rate (Q_m) in relation to the velocity head (Δp) of the gas stream such that Equation 1 is satisfied. This paper will discuss a graphical technique for setting proportional sampling flow rates for a sampling train using a rotameter or an orifice meter as the metering device and a pitot tube as the means for measuring the velocity head. Because arrangements of sampling train components differ, resulting in a difference in treatment, this discussion will limit itself to the gaseous sampling trains shown in the Federal Register (shown later in Figure 1).

Emission Measurement Branch, ESED, OAQPS, EPA, RTP, NC, October 1974

NOMENCLATURE

A_n = cross sectional area of nozzle tip, ft^2

B_{wm} = water vapor in sample gas at meter, proportion by volume

B_{wn} = water vapor in sample gas at nozzle tip, proportion by volume

B_{ws} = water vapor in stack gas, proportion by volume

C_p = pitot tube coefficient, dimensionless

ΔH = orifice meter pressure differential, in. H_2O

K = overall constant

k = proportionality constant, dimensionless

K_m = orifice meter constant, $\frac{ft^3}{min}\left[\frac{(\text{in. Hg})(lb_m/lb_m\text{-mole})}{(°R)(\text{in. } H_2O)}\right]^{1/2}$

K_p = pitot tube constant, $85.48\ \frac{ft}{sec}\left[\frac{(\text{in. Hg})(lb_m/lb_m\text{-mole})}{(°R)(\text{in. } H_2O)}\right]^{1/2}$

M_m = molecular weight of sample gas at meter, lb_m/lb_m-mole

M_s = molecular weight of stack gas, lb_m/lb_m-mole

Δp = velocity head of stack gas, in. H_2O

P_m = absolute meter pressure, in. Hg

P_n = absolute pressure at nozzle tip, in. Hg

P_s = absolute stack gas pressure, in. Hg

Q_m = volumetric flow rate at meter, ft^3/min

Q_n = volumetric flow rate at nozzle tip, ft^3/min

T_m = absolute meter temperature, °R

T_n = absolute stack gas temperature at nozzle tip, °R

T_s = absolute stack gas temperature, °R

v_n = velocity of sample gas stream at nozzle tip, ft/sec

v_s = velocity of stack gas stream at measuring point, ft/sec

60 = conversion factor, sec/min

DEVELOPMENT OF GENERAL EQUATIONS

General equations that relate the velocity head readings(Δp) to the flow rate meter readings will be developed in this section. The velocity at a point within the stack cross section as measured by a pitot tube is given by the equation:

$$v_s = 60\ K_p\ C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}} \tag{2}$$

The velocity v_n can be written in terms of volumetric flow rate as:

$$v_n = \frac{Q_n}{A_n} \tag{3}$$

and, assuming that moisture is the only condensible matter, the relationship between the flow rate (Q_n) at the nozzle tip and the flow rate (Q_m) at the flow meter is:

$$\frac{Q_n(1 - B_{wn})\ P_n}{T_n} = \frac{Q_m(1 - B_{wm})\ P_m}{T_m} \tag{4}$$

Since the conditions at the nozzle tip and at the measuring point within the stack are identical, it follows that:

$$P_n = P_s \tag{5}$$

$$T_n = T_s \tag{6}$$

$$B_{wn} = B_{ws} \tag{7}$$

The flow rate through an orifice meter is given by:

$$Q_m = K_m \sqrt{\frac{T_m \Delta H}{P_m M_m}} \tag{8}$$

For a sampling train using an orifice meter, the general equation that relates Δp to ΔH for setting proportional sampling rates is obtained by substituting Equations 2 through 8 into Equation 1:

$$\Delta H = \frac{60^2 k^2 K_p{}^2 C_p{}^2 A_n{}^2}{K_m{}^2} \quad \frac{P_s T_m M_m (1 - B_{ws})^2}{P_m T_s M_s (1 - B_{wm})^2} \quad \Delta p \tag{9}$$

Note that when $k = 1$, Equation 9 reduces to the isokinetic equation.

For a sampling train using a rotameter, the general equation that relates Δp to Q_m for setting proportional sampling rates is obtained by substituting Equations 2 through 7 into Equation 1:

$$Q_m = 60\ k\ K_p C_p A_n \quad \frac{(1 - B_{ws})\ T_m}{(1 - B_{wm})\ P_m} \quad \sqrt{\frac{P_s \Delta p}{T_s M_s}} \tag{10}$$

The reason for using this form instead of one relating Δp to the rotameter reading is that the latter equation becomes complicated since most commonly used rotameters are viscosity dependent.

EVALUATION OF GENERAL EQUATIONS

Equations 9 and 10 must be evaluated for a specific sampling train and sampling source. Considering the arrangement of the sampling train components shown in Figure 1 and the conditions of most sampling sources, the

following terms can be considered to remain as constants or nearly so: C_p, A_n, B_{ws}, T_s, T_m, M_m, P_s, and P_m. Because a desiccant is used in the sampling train, B_{wm} can be considered to be negligible, i.e. zero. Combining these terms with the proportionality constant k and the other constants, 60 and K_p, into an overall constant K, Equations 9 and 10 can be rewritten as:

$$\Delta H = K \Delta p \tag{11}$$

$$Q_m = K\sqrt{\Delta p} \tag{12}$$

The construction of graphs to aid in the setting of proportional rates will now be discussed for Equations 11 and 12.

CONSTRUCTION AND USE OF GRAPHS

Since size ranges of orifice meters and rotameters vary, examples using a rotameter flow range of 0 to 10 ft^3/hr and an orifice ΔH range of 0 to 10 in. H_2O corresponding to 0 to 10 ft^3/hr will be used to illustrate the technique. In addition, a possible Δp range of 0.001 to 10 in. H_2O will be used.

Equation 11

The operation of Equation 11 is best carried out by a nomograph. To construct the nomograph:

1. Position two log scales, two cycles for ΔH and four cycles for Δ, parallel to each other in the manner shown in Figure 2. Label the scales as shown.
2. Locate the intersects A and B as shown in Figure 2. Then draw the K-factor line.

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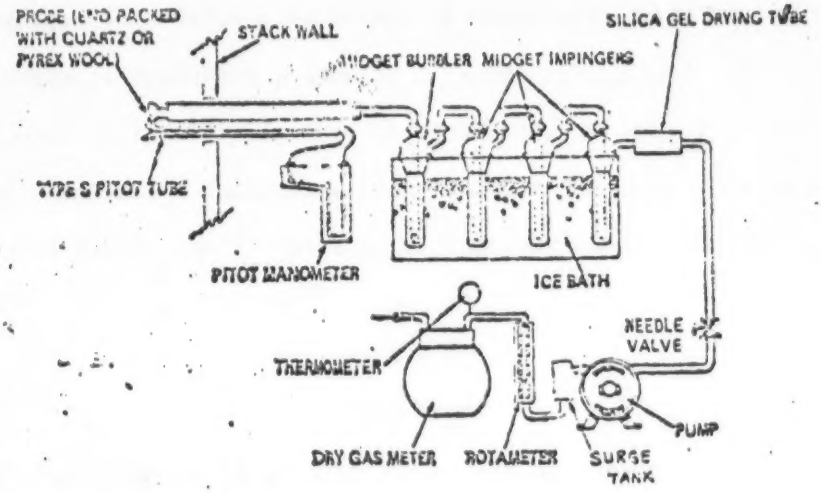
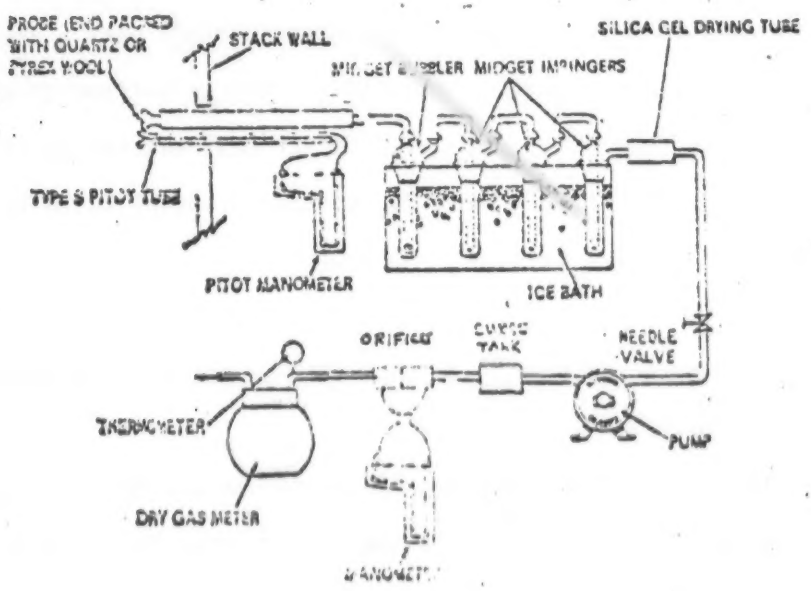


SAMPLING TRAIN WITH ROTAMETER



SAMPLING TRAIN WITH ORIFICE

Figure 1. Schematic showing arrangement of sampling train components.

To use this nomograph:

1. Determine from a rough preliminary traverse the minimum and maximum Δp's. Assume, for this example, that the values are 0.1 and 0.4 in. H_2O, respectively.
2. Align the midpoint of the minimum and maximum Δp's from step 1 (example: 0.25 in. H_2O) with the midpoint of the orifice meter flow range (example: ΔH = 5 in. H_2O), or some other convenient ΔH, and determine the pivot point P on the K-factor line as shown in Figure 3.
3. Align minimum and maximum Δp's with pivot point P to check if the corresponding ΔH's will fall within the flow range of the orifice meter. Allow some leeway on both sides as a safety factor. If necessary, reset the pivot point using a more suitable ΔH.
4. During sampling, determine ΔH from Δp's of the pitot tube and adjust sampling rate accordingly.

Note: The allowable range of flow rate through the collector system should also be considered. Too large a flow rate will cause carryover, while too low a flow rate will sometimes cause inefficient collection. If sampling equipment is properly engineered, the flow meters will adequately cover the allowable range through the collector system and the median velocity pressure should be aligned with the nominal rated flow through the collector.

Equation 12

The operation of Equation 12 is also best carried out by a nomograph.

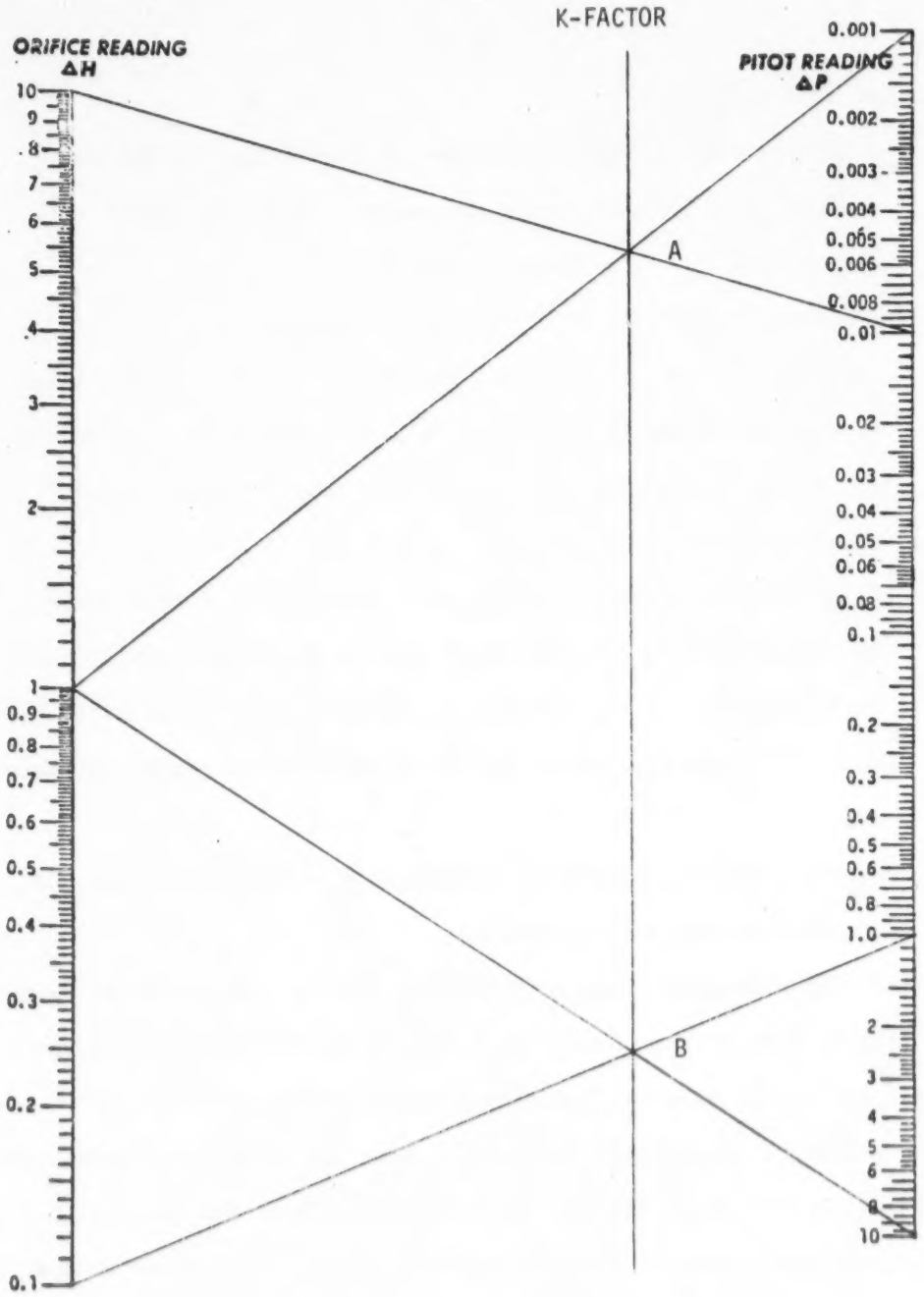


Figure 2. Nomograph construction for Equation 11.

The steps in construction and use of the nomograph are identical to that of Equation 11, except that a Q_m scale replaces the ΔH scale and the K-factor line is now midway between the two log scales. If the rotameter scale does not read directly in cubic feet per hour, corresponding scale readings may be substituted for Q_m via a calibration curve. All of this is illustrated in Figures 4 and 5 in conjunction with Table 1.

Table 1. EXAMPLE ROTAMETER CALIBRATION

Tube reading	Q_m, ft^3/hr	Tube reading	Q_m, ft^3/hr	Tube reading	Q_m, ft^3/hr
25	11.07	12	4.53	5	1.33
20	8.61	10	3.60	4	0.916
18	7.59	8	2.65	3	0.535
16	6.49	7	2.20	2	0.234
14	5.50	6	1.76		

GUIDELINE FOR APPLYING PROPORTIONAL SAMPLING

The need for sampling proportionately is a function of the variation of the pollutant concentration with respect to velocity. Since this relationship is not generally known, a sampling rate proportional to the stack velocity will give the desired time integrated average pollutant concentration.

On a practical scale, a constant sampling flow rate will most likely meet the proportionality requirement in sources under steady state operations, e.g., power plants, municipal incinerators, and cement plants. As a rule of thumb, a constant flow rate may be used when velocity variations do not exceed 20 percent from the average. Beyond this, the sampling flow rate

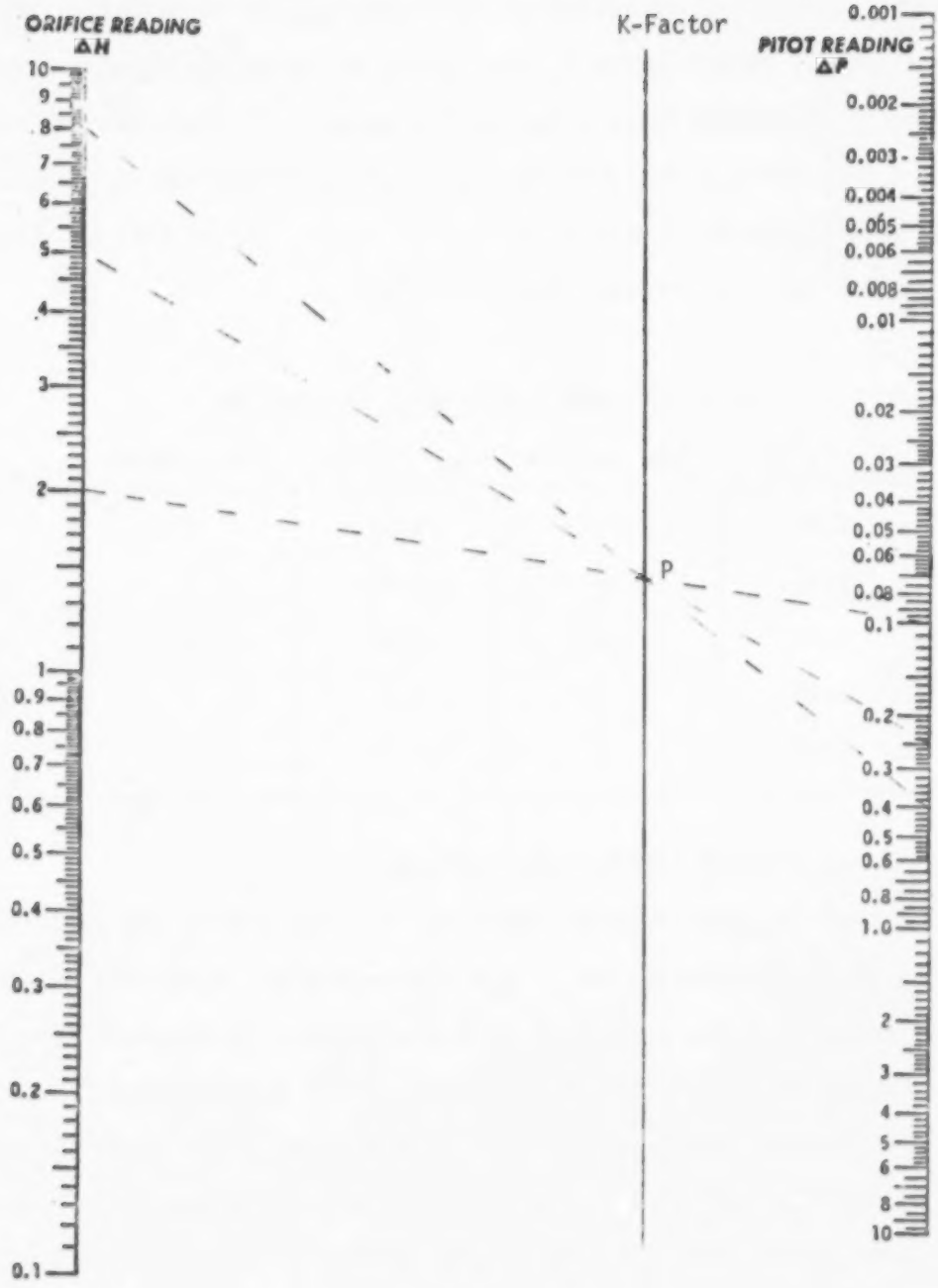


Figure 3. Determining suitable pivot point for setting proportional flow rates.

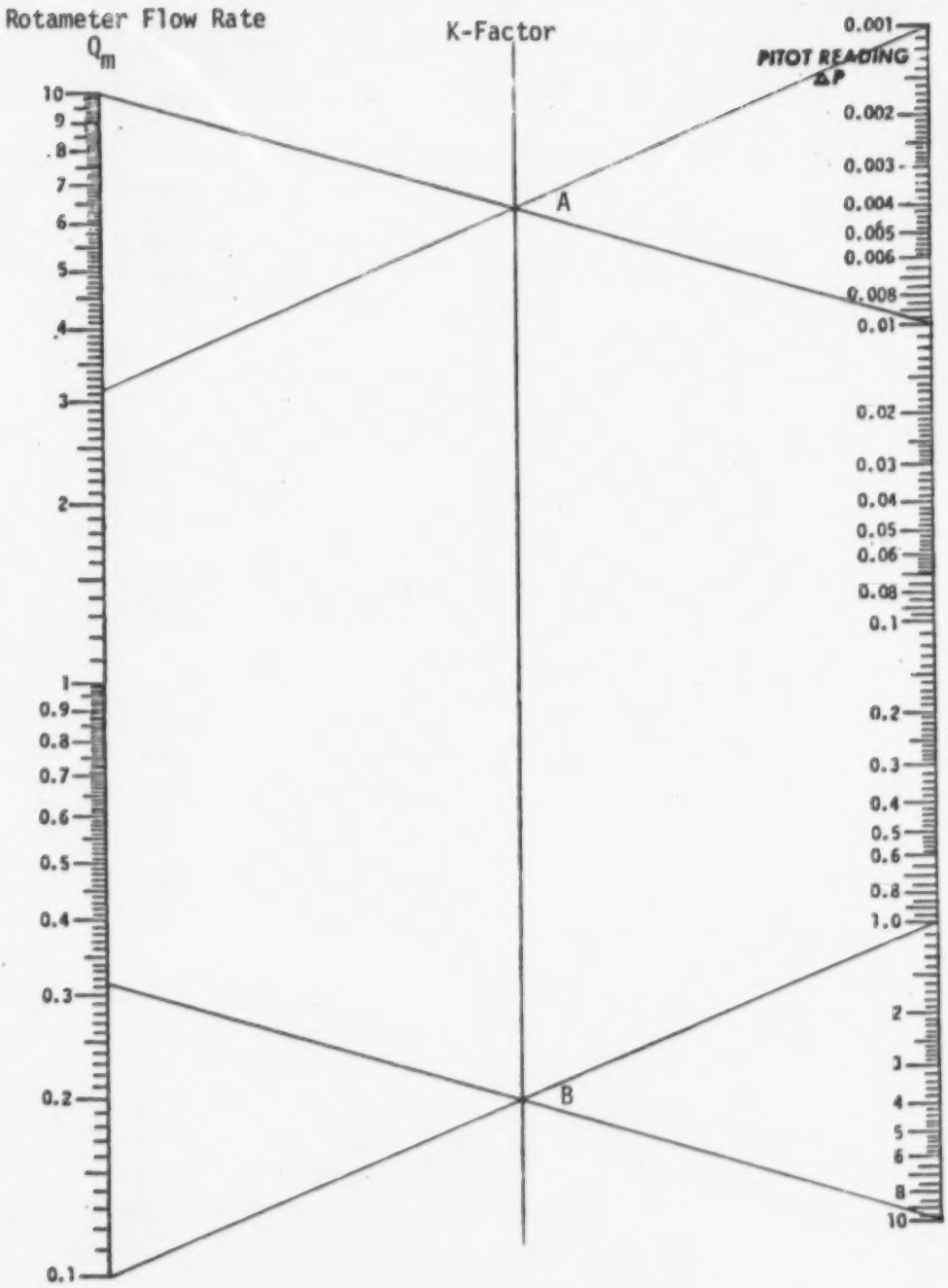


Figure 4. Nomograph construction for Equation 12.

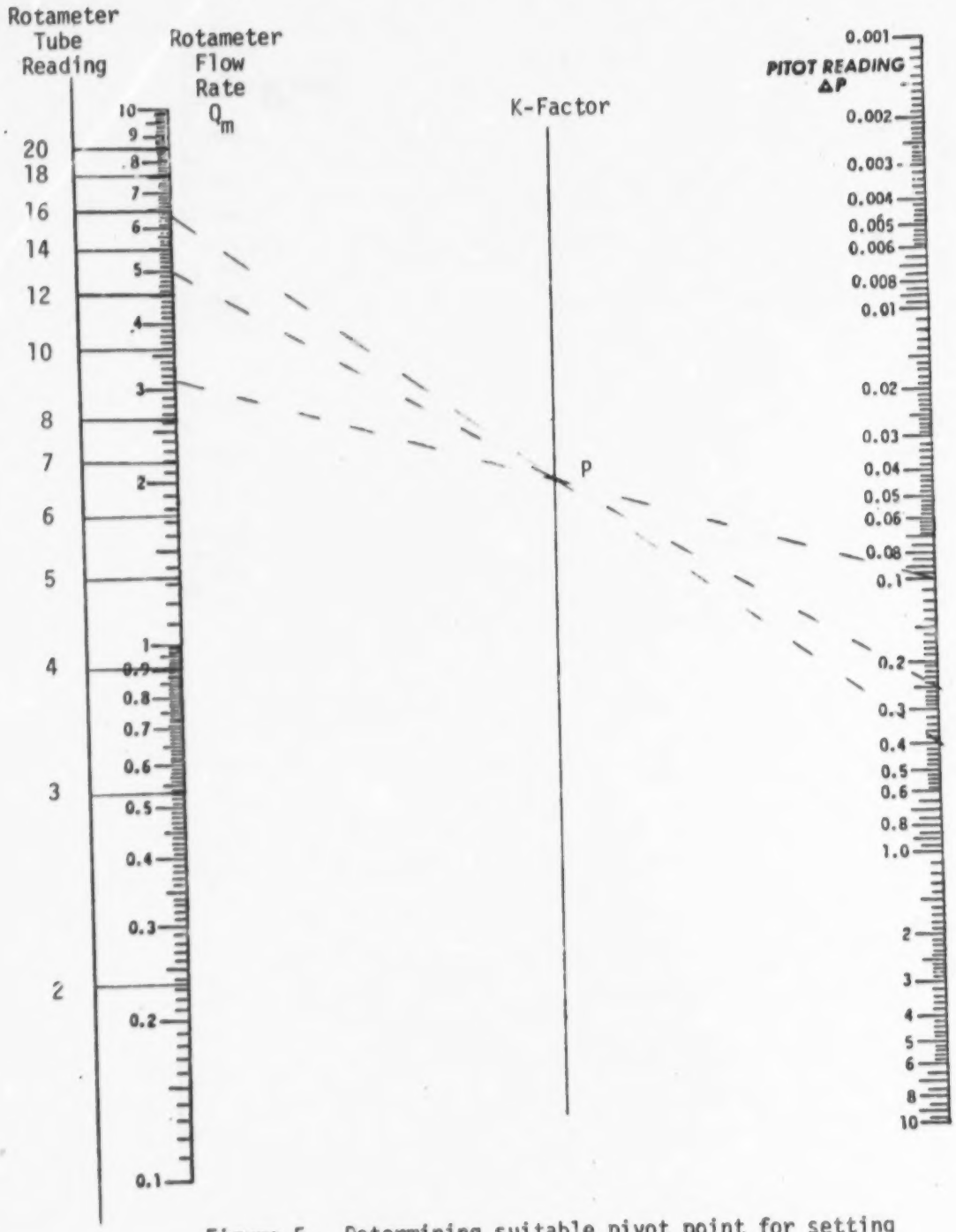


Figure 5. Determining suitable pivot point for setting proportional flow rates for Equation 12

should be regulated in relation to the velocity such that the proportionality constant k varies no more than 20 percent from the average.

SUMMARY

A graphical technique for setting proportional flow rates when sampling for gaseous pollutants with sampling trains utilizing either an orifice meter or rotameter has been discussed. Steps for constructing nomographs and their use have been outlined.

REFERENCES

1. Standards of Performance for New Stationary Sources. Federal Register. Vol. 36, No. 247, Thursday, December 23, 1971.